

Internationale Kommission für die Hydrologie des Rheingebietes

International Commission for the Hydrology of the Rhine Basin

**Impact of changing water demand on the transboundary Rhine River basin
water balance and flow under climate change**

**Socio-economic scenario project (2023-2025) on data collection,
Rhine basin narratives co-design and scenario modelling and
assessment**

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Summary

The Rhine River Basin is increasingly vulnerable to extreme drought events, driven by climate change and evolving socio-economic pressures. These developments pose significant challenges to existing low-flow and drought management practices across national borders.

In response, the *International Commission for the Hydrology of the Rhine Basin* (CHR), in collaboration with the *Central Commission for the Navigation of the Rhine* (CCNR), the *International Commission for the Protection of the Rhine* (ICPR), and the EU Horizon-funded STARS4Water project, launched the Socio-Economic Scenarios (SES) Project (2023–2025). This two-year initiative aimed to provide information for policy and planning on transboundary water resources management by delivering science-based insights into future surface water availability, demand, and allocation under plausible future scenarios, while fostering transboundary cooperation and raising awareness of potential water shortages.

Key activities included collection of socio-economic data, co-designing shared socio-economic narratives, improving the IWRM Rhine Modelling Framework and simulating and assessing scenarios on future water resources availability and water use.

The project was co-designed with input from the three Rhine Commissions and STARS4Water partners, ensuring that stakeholder perspectives were central to the development of scenario narratives and the identification of key questions related to future water stress. Three socio-economic scenarios were developed:

1. *Rhine Sustainable Community* – centred on sustainability and collaborative governance
2. *Rhine Middle of the Road* – reflecting moderate socio-economic growth and policy continuity,
3. *Rhine Economic Growth* – prioritizing economic expansion with higher resource demands.

These scenario narratives were paired with regional climate projections to explore combined biophysical and socio-economic futures.

To support the scenario development and robust modelling, the project compiled a comprehensive dataset from global, EU, national, and local sources. This included environmental data (precipitation, temperature), water infrastructure data (reservoirs) and socio-economic data (population growth, urbanisation, GDP). A selection of these datasets were used to update and parameterize the *Rhine IWRM Modelling Framework* capable to simulate water balances and low-flow conditions across the Rhine Basin.

The scenario narratives were translated into quantitative model inputs, defining key parameters for water demand, water use, infrastructure, and allocation rules. Climate change projections were integrated, and simulations were run to assess future surface water availability, sectoral shortages, and low-flow discharges at key locations in the basin. The *IWRM Rhine Modelling Framework* addresses key stakeholder concerns, such as sector-specific shortages and seasonal water stress.

Key findings of the IWRM Rhine model simulations of the KNMI'23 climate scenarios in combination with the novel co-designed socio-economic scenarios for the situation 2050 in the transboundary Rhine basin are:

- The climate change indicated that changes in glacier and snow melt alternate discharge regimes. Dry summers that are currently considered exceptional, are likely to become more frequent causing a higher risk of low flows.
- Socio-economic developments in the basin will lead to change in water demand and use: while irrigated agricultural water use is expected to increase, domestic and industrial water use can rise or decline, depending on sector specific developments and climate change impact. Largest water demand for irrigation is in the Upper Rhine subbasin area, while industrial water demand is major in the Lower Rhine subbasin. In the Delta Rhine subbasin flushing for preventing saltwater intrusion is the major water user and will further growth due to sea level rise.
- Rising water demand accelerates water stress: combined climate change and socio-economic scenarios show increasing water shortages, especially under pathways like the one in the Economic Growth scenario combined with severe climate change scenario Hd2050, intensifying competition among water use sectors.

These results highlights the growing influence of water demand and use in shaping future sustainable water management and dealing with low-flow conditions from source to sea —not only nationally but also across borders. Water allocation rules and prioritization of water among sectors or across countries as well as re-use (including return flow to the river) require more attention and dialogue: clear rules for prioritizing water among sectors and countries at the river basin level are currently absent, but essential towards the future to ensure equitable distribution during scarcity, considering seasonal variability and sectoral specific needs.

The findings of the SES project underscore the importance of transboundary coordination and adaptive governance in managing future droughts and water scarcity in the Rhine Basin. It contributes in raising awareness among stakeholders on water allocation, prioritization, and the risks of future water shortages. The project provides valuable information for fostering policy dialogue and basin-wide planning efforts such as the updating the Rhine River Basin Climate Adaptation Strategy of the ICPR.

In light of the above, recommendations are made for continued scenario-based planning to anticipate diverse futures, strengthened data sharing and joint modelling efforts, and deeper stakeholder engagement in SES research on enhanced preparedness for droughts and freshwater availability to support river basin planning and informed decision making on necessary actions.

Glossary of key terms

The Glossary presents the key terms and definitions used throughout this report. These terms are central to understanding the dynamics of climate and socio-economic drivers, water-related processes, and governance mechanisms within the Rhine basin, in context of this project. By clarifying the terminology, this glossary aims to support consistent interpretation and facilitate interdisciplinary understanding across stakeholders involved in water management, policy-making, and research.

Term	Definition
Climate driver	A natural factor that influences the climate system, such as greenhouse gas emissions, solar radiation, or land cover change, affecting hydrological patterns.
Drought	A prolonged period of below-average precipitation that results in water shortages in soil, rivers, reservoirs and groundwater.
Low flow	Refers to the condition when river discharge is significantly reduced, typically during droughts.
Scenario	A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios include both qualitative assumptions (based on narratives) and quantitative information on driving forces and impacts. The scenarios for the Rhine basin describe the future water resources availability and water use based on climate change projections and future water demands of socio-economic developments.
Scenario narrative	Scenario development typically starts with one (or more) narrative(s), which describe(s) mostly qualitatively both the changes that are likely to occur and the consequences of those changes. A narrative provides context, motivations and assumptions that help decision-makers and other actors understand how and why a particular future might unfold.
Socio-economic driver	A human-induced factor that shapes water demand and management, including population growth, economic development, urbanization, and policy decisions.
Water allocation	The process of distributing available water among competing users and uses, often governed by legal and institutional frameworks such as priority rules among use(rs). (In this report we focus on: domestic, industrial, agriculture and this order in ranking of priority in supply).
Water availability	Water availability is directly related to how much annual precipitation the area receives and addresses the portion of the total amount of annual water volume that can be abstracted from surface water . In this report quantitative analyses focus on the total volume of surface water from River Rhine, tributaries of the River Rhine and major surface water reservoirs in the basin.
Water consumption fraction	The fraction of water supplied that is consumed by different sectors . (In this report quantitative analyses focus on the following water consumption: domestic, industrial and irrigated agriculture water use).
Water demand	The total amount of water required by various sectors. (In this report quantitative analyses focus on the following water demand: domestic, industrial and irrigated agriculture water use, and for the Rhine Delta specifically: flushing and maintaining water levels).
Water governance	The set of rules, institutions, and processes that determine how water resources are managed and allocated.

Term	Definition
Water infrastructure	Physical systems such as dams, reservoirs, pipelines, and treatment plants that support water supply and management.
Water return fraction	The fraction of water supplied that is not consumed by different sectors but is returned to the river after use, e.g. after passing waste water treatment plants.
Water scarcity	A situation where water demand exceeds availability, leading to stress on ecosystems, human life and economy.
Water security	The reliable and sustainable access to sufficient quantities of acceptable quality water for health, livelihoods, and ecosystems.
Water shortage	Lack of available water to meet demand.
Water stress	The pressure on water resources due to high demand relative water availability.
Water supply	The actual volume of water provided to meet demand, influenced by infrastructure, climate, and policy. In practice this volume can be restricted by abstraction rates from pumps or pipes. (In this report quantitative analyses focus on water supply for domestic, industrial and irrigated agricultural water use and its limitations by low flow discharges in the River Rhine and its tributaries and surface water reservoirs and lakes. Permits, max. pump capacity or other limitations for water supply are not taken into account).

List of abbreviations

Abbreviation	Definition
AQUASTAT	FAO's global water information system
BBSR	Bundesinstitut für Bau-, Stadt- und Raumforschung (Germany)
BfG	Federal Institute of Hydrology (Germany)
BNPE	Base Nationale des Prélèvements d'Eau (France)
CCNR	Central Commission for the Navigation of the Rhine
CHR	International Commission for the Hydrology of the Rhine Basin
CORRECTIV	German investigative journalism platform
Deltares	Dutch institute for applied research in water and subsurface
DESTATIS	German Federal Statistical Office
DTK	Deutsches Talsperrenkomitee
EEA	European Environment Agency
E-flow	Ecological flow (minimum flow required for ecosystems)
EG LW	Expert Group on Low Water, part of the ICPR
EOBS	European Observational Dataset
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GIQ	Navigable Low Water Level
GIW	Equivalent Low Water Level (navigation benchmark)
GRanD	Global Reservoir and Dam Database
GRDC	Global Runoff Data Centre
HCLIM	ICPR Expert Group on Climate (Hydrological Climate scenarios)
ICPR	International Commission for the Protection of the Rhine
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resources Management
KNMI	Royal Netherlands Meteorological Institute
LHM	Landelijk Hydrologisch Model (i.e. Dutch national hydrological model)
LST	Land Surface Temperature
Modflow	Groundwater modelling software
NHI	Dutch National Hydrological Instrument
NM10Q	Normal Minimum Discharge over 10 days
NM7Q	Normal Minimum Discharge over 7 days
OECD	Organisation for Economic Co-operation and Development
PBL	Netherlands Environmental Assessment Agency
PNACC	French National Climate Change Adaptation Plan
RACMO	Regional Atmospheric Climate Model
RCP	Representative Concentration Pathway
Rheinblick2027	CHR study on future Rhine River basin hydrology

Abbreviation	Definition
Rhine 2040	ICPR program for future Rhine basin planning
Ribasim	Model software platform for integrated river basin management and water allocation simulation
Ribasim Rhine model	Integrated river basin management and water allocation simulation model application for the Rhine River basin
RTC-tools	Real-Time Control tools – model software platform for control and optimization of a wide range of water systems like reservoir cascades, canal systems.
RWS	Rijkswaterstaat
SES	Socio-Economic Scenarios
SFEO	Swiss Committee on Dams
SLR	Sea Level Rise
SSP	Shared Socioeconomic Pathway
STARS4Water	“Supporting Stakeholders for Adaptive, Resilient and Sustainable Water Management”, a collaborative project funded under the Horizon Europe Framework Programme.
STOWA	Foundation for Applied Water Research (Netherlands)
SVGW	Schweizerischer Verband für Wasser, Gas und Wärme (Switzerland)
TRACC	Trajectoire d'Adaptation au Changement Climatique (France)
UCLA	University of California, Los Angeles (Circa 2015 reservoir dataset)
WFD	Water Framework Directive
Wflow	Model software platform for distributed hydrological modelling
Wflow Rhine model	Distributed hydrological model application for the Rhine River basin
WWOptII	German research project on reservoir management and low flow discharges (ongoing)

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1 Introduction

1.1 Setting the scene

The Rhine River is an important source of water during dry summers across the riparian countries (Figure 1). Changes in the discharge of the Rhine River potentially have a large impact on all water-dependent sectors. Several studies (Stahl et al., 2022; Buitink et al., 2023; ICPR, 2024) have indicated that climate change is causing shifts in precipitation and temperature patterns. Related droughts, floods, and high-water temperatures may negatively impact the flow regime of Rhine river and its tributaries as well as water usage (ICPR, 2025abc). However, they did not include the possible impact of changing water demand in the Rhine basin, although this might significantly impact the Rhine discharges as indicated by Ruijgh et al. (2019).

In 2014 the CHR organised its first seminar in on the socio-economic influences on the discharge of the Rhine river. Since then Socio-Economic Scenarios is one of the research lines of the CHR. The SES-research line of the CHR aims to provide scientific-based information on balancing water availability, demand and use, as well as on allocation, and shortages for the Rhine basin in a transboundary context based on plausible future scenarios. Additionally, it aims to create public awareness of future water shortages under plausible future scenarios.



Figure 1: Rhine River basin and riparian states (Schulte-Wülwer-Leidig et al, 2018; ICPR, 2020)

Results are also input for updating the Rhine River basin climate adaptation strategy (ICPR, 2025b), facilitating countries to decide on necessary actions to address issues and be jointly, on the transboundary level, better prepared for future water scarcity challenges during dry periods.

1.2 CHR's Socio-Economic Scenarios project in 2023 – 2025

In 2023, the CHR launched a new SES project to provide science-based insights into future surface water availability, demand, and allocation under plausible future scenarios, while fostering transboundary cooperation and raising awareness of potential water shortages. (in short: the SES project (2023-2025)). The following overarching questions from the CHR were identified for the project (CHR, 2023):

1. What socio-economic scenarios are already available/in use in the Rhine basin countries? What is the state-of-the-art of socio-economic scenario research ongoing or planned in Rhine basin countries?
2. What scenarios are developed/in use by the IPCC and EU commission? How can they be inspirational for what-if scenarios (see next question)?
3. How to define, prepare and assess scenarios related to water shortage in transboundary context, to create meaningful input for answering question 5 (below)? This research also considers differences among the Rhine countries as well as differences between the main river and its tributaries.
4. How to improve data/set-up data repository? How to improve the Rhine modelling toolbox to assess current and future water availability, water use and water allocation in the Rhine basin? What local datasets are required to improve the CHR existing databases and modelling tools to describe the present situation?
5. How to take joint and informed action to water security based on common understanding of issues, trade-offs, and benefits? In this regard, the CHR focusses on improved system understanding and awareness raising, while the output of questions 1-4 will be input to the various action planning processes, including the Rhine adaptation planning process of the ICPR.

1.3 Collaboration with ICPR, CCNR and STARS4Water

The CHR SES (2023-2025) research team, consisting of researchers from Deltares, has been collaborating intensively with the secretariats, members and scientific representatives of the CHR, ICPR (especially with the ICPR Expert Group on Low Water - EG LW), the CCNR and with the EU-Horizon programme funded STARS4Water project (<https://stars4water.eu/>) to conduct this research, since they have similar ambitions. Under leadership of the CHR and ICPR secretariats, regular meetings took place and different exchanges with the stakeholders were organised to receive valuable input and feedback.

The final draft results were presented at the CHR meeting on March 17, 2025 and in the ICPR climate adaptation workshop on March 19/20th, 2025 in Arnhem. During the workshop participants discussed the signalled issues on balancing water availability and water demand as identified in this SES 2023-2025 project. An interactive presentation and lively discussion on the issues was followed by a workshop with a brainstorm on possible solutions for the Rhine basin, as an input for updating the ICPR climate change adaptation strategy of the Rhine river basin by end of 2025 (ICPR, 2025b).

1.4 About this report

Chapter 2 introduces– the research objectives and approach of the project.

Chapter 3 presents an overview of the current national socio-economic scenarios and an inventory of national water demand data available within the different Rhine Countries, providing input for questions 1, 2, and 4 from the CHR (see in subchapter 1.2).

Chapter 4 introduces the new Rhine transboundary socio-economic scenarios that are co-designed with stakeholders in the project. They are providing input for CHR question 3.

Chapter 5 describes the updates of the Rhine River Basin Scenario Tool. Supported by the EU Horizon STARS4Water project, the tool consists of the Ribasim Rhine model that is now integrated with the Wflow Rhine model and features updated data inputs.

Chapter 6 presents and discusses the results of the different simulation runs with the tool which provides input for CHR question 4.

Chapter 7 discusses what has been achieved, and recommendations for next potential steps.

An extensive **literature list** can be found at the end of this report. More technical background information is available through the provided website links, for example for the Wflow and Ribasim model software manuals and/or the EU horizon STARS4Water deliverables.

More detailed information on the socio-economic narratives can be found in **Annex A**. **Annex B** describes the evaluation and validation of the model in more detail.

2 Research objectives and approach towards better understanding of water resources availability, allocation and use at the Rhine River basin

2.1 CHR's Socio-Economic Scenarios research objectives in 2023 – 2025

The main objectives of the SES project (2023-2025) are:

- To gather data and information about climate change scenarios, socio-economic scenarios and water use from open, global, EU, national, and regional datasets.
- To develop three socio-economic scenarios on the transboundary level based on three different perspectives. The narratives of the scenarios represent three different plausible socio-economic futures in the Rhine River basin under climate change.
- To improve the IWRM Rhine Modelling Framework, which includes a Rhine integrated river basin management and water allocation model for the Rhine (the Ribasim Rhine model) coupled with a Rhine hydrological model (the Wflow Rhine model).
- To translate the socio-economic narratives to model input and combine them with climate change scenarios model input.
- To make model simulations, and analysing the results regarding the impact on water balances in the Rhine (sub)basin(s) and Rhine River low flows at various locations.
- To provide recommendations for next steps based on the outcomes of above activities.

2.2 Gathering data and information

The memo by De Bruin & Edler (2023), which initiated the project activities in 2023, documents the preliminary data and information gathering for the exploration of socio-economic scenarios in the Rhine riparian countries. The memo provides an overview of Representative Concentration Pathways (RCPs) and Shared Socio-Economic Pathways (SSPs) and examines the socio-economic scenarios (SES) currently available or in use across the Rhine basin countries. Additionally the memo includes an initial inventory of ongoing or planned SES research in Rhine basin countries, primarily based on interviews with CHR members and desktop research. This information has served as input to the follow-up work within CHR SES and collaborative efforts with the EU horizon project STARS4Water and the Rhine Commissions (CHR, ICPR, and CCNR), focusing on scenario development and assessments through model simulations.

During the project, additional data and information on scenarios and water use were gathered through bilateral meetings with the members of the ICPR Expert Group on Low Water (EG LW), supported by the CHR, ICPR, and CCNR secretariats. Input was also exchanged with the Rheinblick2027¹ project team and the WWOptII² study by the Federal Institute of Hydrology (BfG) which focuses on reservoir management and low flow discharges in the Rhine River (Ebner von Eschenbach, A. et al, 2025). These efforts supported the design of scenarios and improvements of the Ribasim Rhine model.

¹ Rheinblick2027 is another CHR research line focusing on the impacts of climate change on the Rhine River discharge

² Potenzialstudien wasserwirtschaftlicher Optionen zur Niedrigwasseraufhöhung für die Rheinschifffahrt

Additionally, STARS4Water established the [STARS4Water meta-data portal \(STARS4Water Metadata Portal – STARS4Water\)](#), which includes over 450 datasets useful for river basin planning and assessment (Schotmeijer et al., 2023). This portal supported the collection of necessary information underpinning the first transboundary socio-economic scenario narratives development and quantification of these narratives, e.g. providing information on datasets on GDP and population growth in the Rhine basin countries.

2.3 Designing socio-economic scenarios for the Rhine River basin

In cooperation with the ICPR, CCNR and STARS4Water the CHR aims to assess the future water resources availability and use in the Rhine River basin as well as the river discharges in 2050 under uncertainties of socio-economic development and climate change. For this assessment, we co-designed three scenarios (see definition below in text box 1) that describe three plausible futures in the basin. They reflect varying socio-economic developments, such as population growth, economic growth, and spatial planning across the Rhine basin countries under climate change. The scenarios were informed by global (e.g., IPCC – RCPs/SSPs scenarios, 2021), European (e.g., EEA 2021- Water resources across Europe), and national sources (e.g., Dutch Delta Scenarios (Van der Brugge & de Winter, 2024)). The scenario development in this project benefitted from the “co-designed scenario narratives” approach developed by STARS4Water (Okruszko et al., 2024).

For the Rhine basin the climate change scenarios are already readily available. These regional climate change scenarios dedicated for the Rhine basin are based on IPCC AR6 and developed by KNMI and Deltares. (KNMI, 2023; Buitink et al, 2023). These scenarios were taken as boundary conditions for the socio-economic scenarios that were newly formulated. Logical combinations (one socio-economic scenario with one climate change scenario) were made.

Following this approach (Figure 2), the current situation (A) was described through the perspective of the biosphere (green), society & economy (orange), and the institutional setting (blue). On these levels, scenarios (B)) were developed describing climate and socio-economic drivers (C)) and adding quantitative information on climate projections and water use(rs) (D)) in the Rhine river basin. All information served as input for modelling water resources availability and river discharges E)).

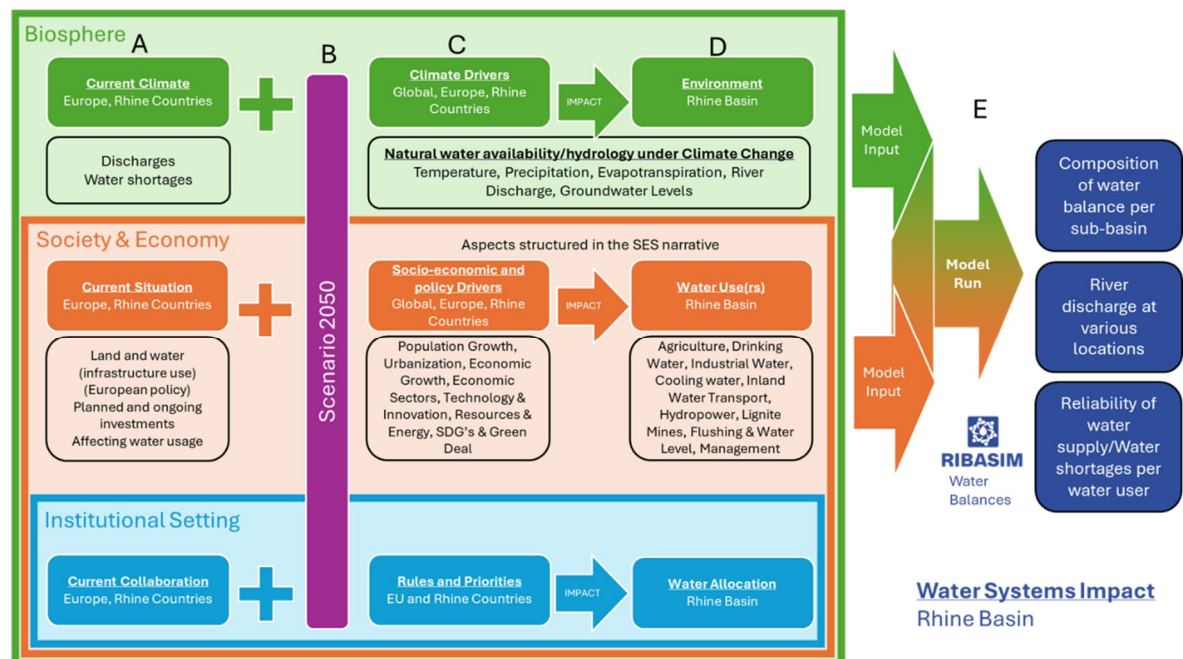


Figure 2: Overview on set-up of developing scenarios for the Rhine basin and how their impacts are evaluated

Text box 1: Definition of scenario

A **scenario** (as defined in this project) is a plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios include both **qualitative assumptions** (based on narratives or storylines) and **quantitative information** on driving forces and impacts. The scenarios for the Rhine basin describe the future water resources availability and water use based on climate change projections and future water demands of socio-economic developments.

Scenario development typically starts with one (or more) **narrative(s)**, which describe(s) mostly qualitatively both the changes that are likely to occur and the consequences of those changes. A **narrative** provides context, motivations and assumptions that help decision-makers and other actors understand how and why a particular future might unfold.

Next step is to develop scenarios by **assigning numbers to the narratives on driving forces and impacts** with the help of models and/or data analysis.

Scenarios cannot be considered as an end goal in themselves; they facilitate strategic discussions. Their goal is not to predict; they do not answer questions such as 'How likely is this?', but rather assist in thought provoking discussions in terms of 'What will we do if this happens?'.

These scenarios could be meaningful in our way of understanding of the water system and in devising water management strategies plans. They are based on a narrative or storyline that has the interest of specific actors (i.e. the Rhine commissions) in their need for information about a certain anticipated change, or issue of development. It is targeted of our knowledge for particular developments / course of action (e.g. agriculture, land cover, demography) and might begin with: "what if..." to explore.

In the context of developing scenarios for the Rhine River basin two major developments or categories are distinguished: climate change and socio-economic change. The first is a plausible and often simplified representation of the future climate, while the other is based on simplified representation of the future socio-economic situation.

For the Rhine basin the climate change scenarios are readily available, incl. datasets for modelling. These regional climate change scenarios dedicated for the Rhine basin are based on IPCC AR6 and developed by KNMI and Deltares. (KNMI, 2023; Buitink et al, 2023).

In addition, as part of this SES project (2023-2025) additional scenarios, covering the socio-economics domain, have been constructed, for explicit use in investigating the potential consequences of socio-economic pressures, often serving as input to for example water demand, water infrastructure and impact models. National trend and exploratory analysis (both in- and outside the water domain) often serve as the raw material for constructing these scenarios. The combined scenarios for the Rhine River basin consists of a combination of climate change scenario and socio-economic scenario, considering interferences and feedback loops. E.g. extreme climate change is combined with increased water use due to high end economic growth in one scenario.

2.4 Modelling framework for IWRM in the Rhine River basin

A modelling framework for Integrated Water Resources Management in the Rhine River basin was set up to assess the sustainable use and allocation of water resources, towards complying with European Union Directives in particular the Water Framework Directive (WFD) and drought management plans. The approach and methodology followed in this project allow for the evaluation of various scenarios and management strategies at the sub-basin level.

It lays the foundation for the necessary modelling framework for the Rhine River basin commissions and other stakeholders to make informed decisions about water resources allocation and use, considering the impacts of low flow and water scarcity and seeking to mitigate them. The new modelling framework enables computational water balances analysis regarding water resources allocation and use and low flow conditions, including the impact of water use, impact of infrastructure and/or water management strategies. The modelling framework consists of the Wflow Rhine model (a hydrological model) and the Ribasim Rhine model (an integrated river basin management and water allocation model). This modelling framework is further named the *IWRM Rhine Modelling Framework*. The structure is shown in Figure 3.

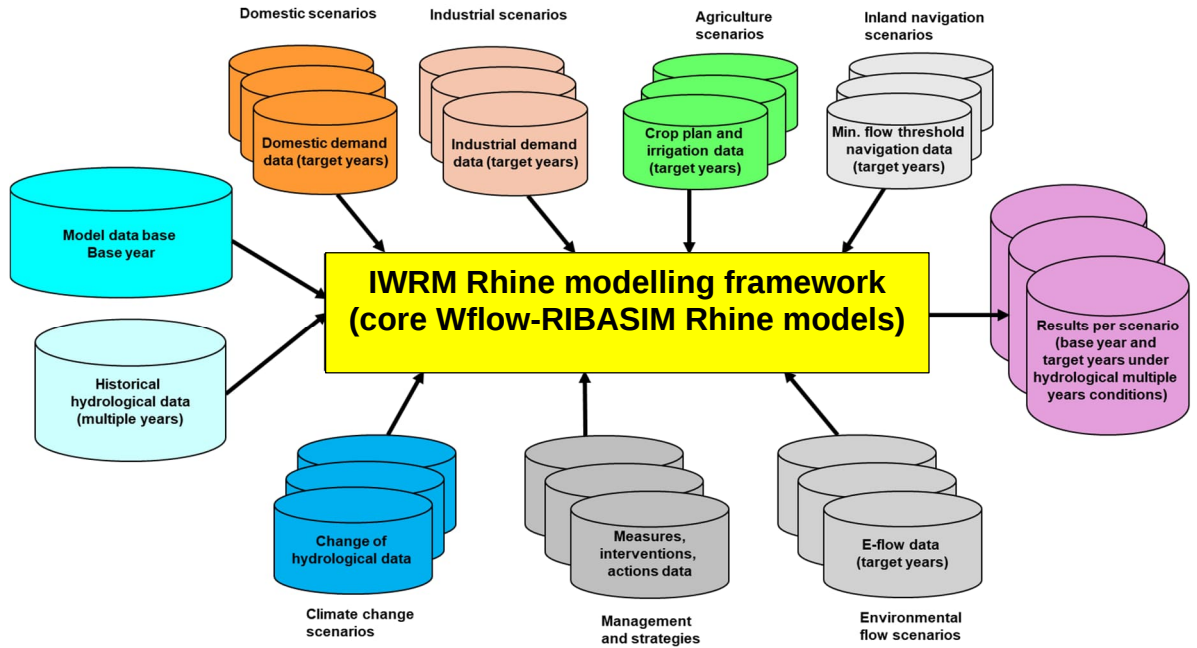


Figure 3: The structure of the IWRM Rhine Modelling Framework that enables scenario analysis in water resources allocation and use and low flow conditions – core are the Wflow Rhine model and the Ribasim Rhine model (grey boxes are not yet applied in this SES project (2023-2025))

The model workflow for making such a quantitative assessment on the water balances on the (sub)basin(s) levels and the flow at various locations along the river and the reliability in the water supply is shown in Table 1Table 2. The modelling workflow is established with support from the EU Horizon STARS4Water project. [RIBASIM](#) is a network-based 0-dimensional water balance model for performing integrated river basin management and water allocation simulations. The previous Ribasim Rhine model (Van der Krogt, 2021) is updated in terms of new software version (including new FEWS user interface, new computational workflows), more recent and/or local datasets, and prepared for running climate and socio-economic scenarios.

The Ribasim Rhine model is coupled with the Wflow_sbm Rhine model for necessary meteorological and hydrological boundary conditions, especially the run-off, precipitation, and evaporation. [Wflow_sbm](#) is a spatially distributed, conceptual rainfall-runoff model, containing a kinematic wave routing approach for lateral subsurface, overland, and river flow processes (Van Verseveld et al., 2024). The Wflow_sbm Rhine model was established to evaluating the impact of regional climate change scenarios (i.e. KNMI'23 scenarios) on the discharges in the Rhine River basin (Buitink et al., 2024).³

³ In CHR's research line "Rheinblick2027", the CHR is conducting detailed research on the (major) impacts of future climate change on the discharge of the Rhine River and its major tributaries based on a multi-model approach and both KNMI'23 and CORDEX regional climate change scenarios. This study takes place from 2024-2027 and will

The grid-based Wflow was also used to calculate the water demand for domestic use, industrial use, and irrigated agricultural water use from surface water. It is assumed that those will affect the Rhine low flows.

Basic model data input describing the current situation (base year and historical hydrological data) can be replaced by alternative datasets describing the future situation to simulate future situations in water balances and flows.

Table 1: Wflow and Ribasim models are the core for IWRM Rhine modelling tool

	Wflow	Ribasim
Model	Distributed gridded hydrological model inc. option for simulating water demand	Integrated river basin management and water allocation simulation model
Schematization	 Catchment grid cell schematization	 Water System node-link schematization
Input data	Rainfall, evaporation, catchment characteristics	In- and Output from Wflow: Discharges catchment Water demand per sector and catchment
Optional	Water demand module	Prioritization in water supply per sector demand, reservoir management, and other management measures and strategies
Output	Discharge timeseries per catchment Water demand per sector per 1km ² grid cell and per catchment	Composition of the water balances of (sub) basin, river discharges, water storages changes and supply reliability,

Future perspectives for the IWRM Rhine modelling framework

A new module to assess the current and future agricultural water demand and irrigated water use is still under development in the STARS4Water project (PhD research project 2022-2026). It is based on a hybrid modelling approach using earth observation data and machine learning techniques in the context of the Wflow model platform and advanced statistical analyses. This module will be available in 2026, after the lifetime of the SES2023-2025 project.

Additionally, an e-flow assessment tool is under development in the STARS4Water project to support the evaluation/integration of ecological flow needs in the modelling and can be connected to the model framework in second half of 2025. Similar is valid for minimum threshold for river discharge for inland navigation.

deliver an ensemble of future projections for the river flow in the Rhine River basin. In the SES 2023-2025, we make use of the hydrological timeseries based on the KNMI'23 scenarios and wflow model, which were already available. In a later stage, additional model runs can be made based on the hydrological timeseries of any other hydrological model and other climate change scenarios, when they become available.

Another update that is possible would be the new water demand datasets on drinking water and industrial water demand that are under development based on the latest global datasets available about population, GDP, etc., leveraging the STARS4Water metadata portal ([STARS4Water](#)).

Deltares envisions that the results of current ongoing research or dataset improvements will be included in the modelling framework in the event of future extensions of the SES project or similar initiatives, to strengthen the framework further.

2.5 A brief introduction to the methodology for water balances calculations

The computational methods for water balances are described in detail in the Ribasim user manual and technical reference manual (Van der Krogt et al., 2013; Van der Krogt, 2008). In this subchapter we describe the basic modelling principles to provide initial technical background for the interpretation of the model improvements (described in Chapter 5) and the modelling results (described in Chapter 6).

To simulate water balances, we use a target level for water demand in the current situation and for a specific year. In this study the specific year is the year 2050. The water demand is estimated through simulations incorporating information on water needs for domestic, industrial and agriculture sectors. The water demand is calculated at grid level (1x1 km²) and aggregated to the subbasin level. Since the focus is on future low flow situations we select a target level that represents the water demand under extreme dry conditions as water demand tends to peak in this situation. For example, irrigation water demands will significantly increase in periods of droughts.

These water demand are benchmarked against a range of hydrological years, including dry, extreme dry, wet, extreme wet and normal years, by running simulations over long (multiple years) time series that include the occurrence of dry and wet periods (Figure 4). The hydrological time series are available at subbasin level and at sub-subbasin level, both the current and the year 2050. The timeseries are generated using the Wflow Rhine model) at 1x1 km² grid cells.

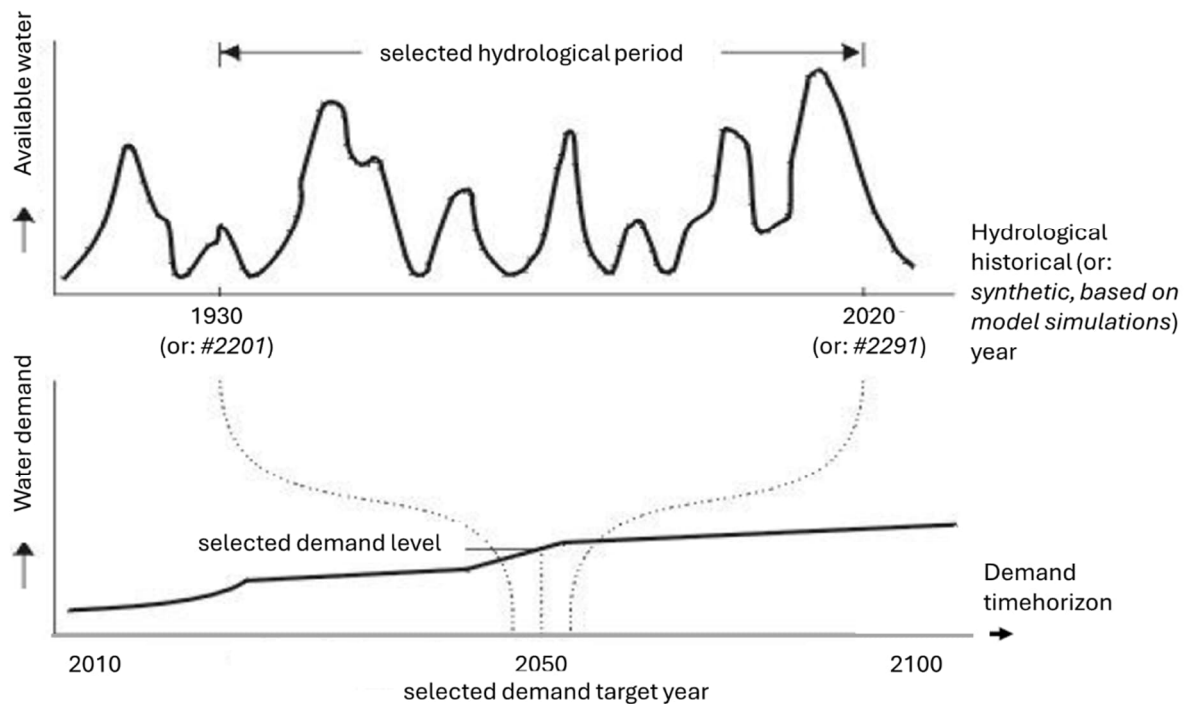


Figure 4: Water balance simulation principle – the selected water demand target year is benchmarked against the selected hydrological period that represents a range of hydrological years (normal, wet, dry, extreme dry, etc.) (adopted from Van der Krogt, 2011)

For water balances analyses at transboundary basin level and sub-basin level as carried out in this project, a simulation time step of 10-day is an appropriate and robust timestep for the level of detail. By using a 10-days timestep the model ensures that the flow is “complete” at each step, meaning that discharge from upstream locations has sufficient time to propagate through the system. This approach enhances the model’s robustness and stability across a range of hydrological scenarios, including low-flow periods and delayed transport. Additionally, the 10-day time-step allows for accurate representation of intramonth variability, which would be lost with a coarser monthly timestep.

Within each time step, the water demand of the water sectors is determined, resulting in targets to abstract water from the river for water supply. All at the subbasin level. Then, the water is allocated to the users according to the abstract targets (the water demand request), based on water availability, i.e. taking into account sufficient flow in the river, operation rules and water allocation priorities.

Water allocation to users can be done in several ways, for example, water is allocated on a “first come, first served” basis along the natural flow direction. This allocation principle can be amended by rules which, for example, allocate priority to particular users, or which result in an allocation proportional to demand. In this study we worked with a fixed order for water allocation to satisfy demand: 1. Domestic water use, 2. Industrial water use, 3. Agricultural water use.

A fraction of the water that is allocated to the water demand of the water users, will be consumed, the remaining is returned to the river flow after use, and is available for users downstream of the return flow and/or next in priority.

In this study, we make water balances on the level of the total Rhine basin as well as subbasin level.

Figure 5 illustrates the fundamental relationship between water availability and water demand in the context of the IWRM Rhine Modelling Framework simulations and evaluation of modelling results in this project. When water demand exceeds water availability, the difference between the two results in a water shortage. This shortage reflects unmet water demand across sectors.

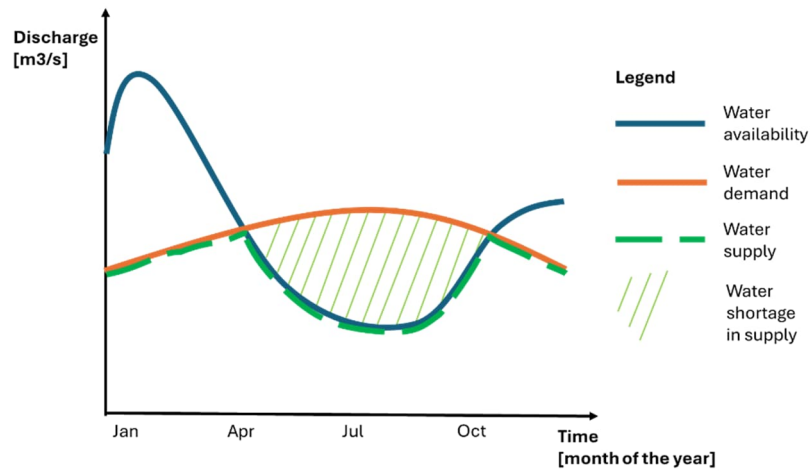


Figure 5: Water balance simulation principle – the selected water demand target year is confronted with the water availability to identify water shortages in supply

3 First results on inventory of SES and of available national water demand data

This chapter presents the socio-economic scenarios information and water use and supply data gathered during the project, in cooperation with ICPR, CCNR, and STARS4Water. The collection of national socio-economic scenarios information and national and local data took mostly place by bilateral meetings with representatives of the Expert Group on Low Water, which is part of the ICPR (ICPR, 2022-2025), as many sources are not (yet) open or easily accessible in the public domain or accessible via the internet. These meetings occurred parallel to the process of scenario and model development.

A database and literature archive on socio-economic scenarios, water use and reservoirs data was created. It has been handed over to the CHR secretariat and should be made available —both now and in the future— to relevant stakeholders, including the ICPR and the CCNR. It is intended to be either maintained by the CHR secretariat and/or integrated into the new information system currently being developed by CHR.

Not all datasets referenced in the Tables 2, 3 and 4 in this chapter are provided directly in this report, established database and/or archive. Instead, we cite the primary sources from which they originate, allowing readers to access the original data through those sources. This approach ensures transparency and traceability, while respecting data ownership and licensing.

The data and literature archive is a highly valuable source for research. In the timeframe of the project part of these data and information could be leveraged, analysed, and/or included in the scenario and model improvement in the time frame of this project.

3.1 Inventory national socio-economic scenarios

To contribute to answering CHR research questions 1 and 2, Table 2 provides an overview which global, EU, national, and regional perspectives could be identified in the timeframe of the project. It also indicates their applicability (based on current knowledge) for the Rhine River Basin perspective and translations to water-related transboundary themes.

The table shows that the countries have indicated that they have national socio-economic scenarios (SES) available for their country, except Austria. The national SES often refer to the Shared Socioeconomic Pathways (SSPs), which represent five narratives of socio-economic development, including factors such as technological development, population changes, and economic growth (see Figure 6). At national level, the available socio-economic scenarios in the context of climate impact studies are usually based on a combination of SSP and Representative Concentration Pathway (RCP). The RCPs are pathways for greenhouse gas concentrations into the future, detailed by the level of radiative forcing by 2100. These range from 2.6, 4.5, 6.0, and 8.5 W/m². If a SES of Rhine river basin country is based on SSP and/or RCP, it is indicated in Table 2 as well.

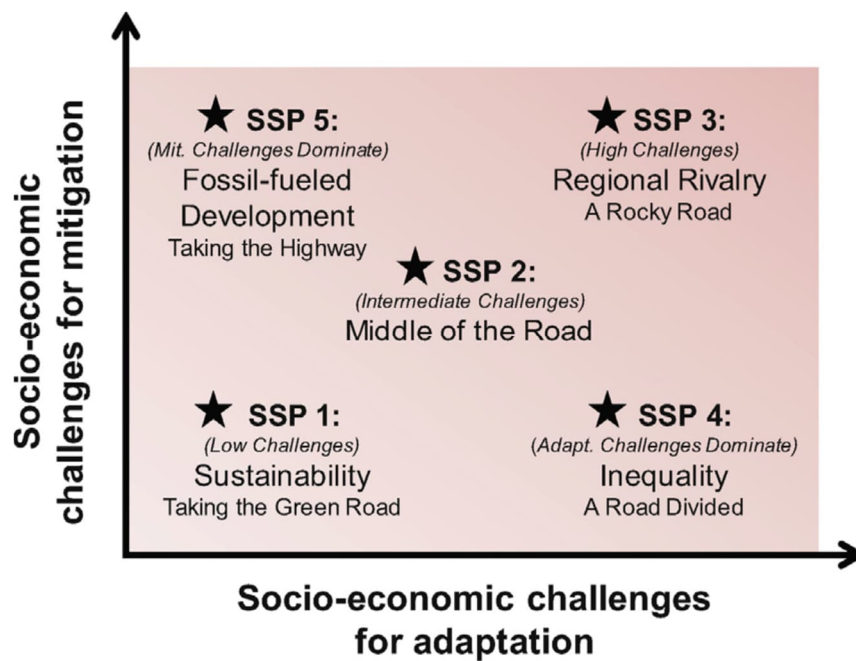


Figure 6: Shared Socioeconomic Pathways mapped by level of mitigation and adaptation challenges (copied from O'Neill et al., 2017)

Chapter 4 describes the first transboundary socio-economic scenarios at river basin level. These scenarios are co-designed with stakeholders in the Rhine River basin, considering the wealth of information and local knowledge available indicated by the national socio-economic scenarios information.

Table 2: Summary of the first inventory of Socio-Economic Scenarios formulated by institutions in the Rhine countries (status end 2024)

Country	SSPs considered	National SES	Time horizon	Further translation required to Rhine basin
Switzerland	SSP1-5	The study started on developing SSP-CH. A methodological approach is detailed. The project started in 2022 and is running until 2025.	Today-2050 and 2050-2100.	Scenarios are under development and describe socio-economic developments in national economy; a further translation to water-related themes must be made.
Austria	SSP1, SSP2, SSP5 (used in WaterStressAT and other scenario-based studies)	WaterStressAT, Graz TU urban water demand study, BOKU/TU Wien land use & water quality study	Up to 2100 (varies by study: 2030–2060, 2050, 2100)	Yes — Rhine basin includes only part of Austria; national studies need spatial downscaling and alignment with transboundary context
Germany	SSP1-5	Three national scenarios have been developed; they do not directly correspond to the SSPs. Three scenarios: Stability; Trend (similar to SSP2); and Dynamic.	Up to 2050	Translated from national to regional perspective, not specific for Rhine Basin.
		BfG Project and Scenarios with selected socio-economic scenarios for the Rhine River in Germany.	2040	Selection of scenarios relevant for the Rhine Basin.
France	<i>Existing global policies, without additional additional measures, global warming of around 3°C by 2100-.</i>	France has adopted a scenario known as the Trajectoire d'Adaptation au Changement Climatique (TRACC): a global warming baseline of : +1.5°C in 2030, +2°C in 2050 and +3°C in 2100 compared with the pre-	2030, 2050, 2100-.	The TRACC has been translated into the 3rd National Climate Change Adaptation Plan (PNACC), published on March 10th 2025. This plan will be rolled out at regional level. Risk prevention plans and planning

Country	SSPs considered	National SES	Time horizon	Further translation required to Rhine basin
		industrial era, i.e. a level of warming in mainland France of around +2°C in 2030, +2.7°C in 2050 and +4°C in 2100. This scenario corresponds to the continuation of existing global policies, with no additional measures.		documents will have to take account of the TRACC and incorporate adaptation to climate change into their prevention and protection measures.
Luxembourg		Public consultation is ongoing along three national scenarios. Not yet clear if/how these are linked to the SSPs and/or are more visionary goals.	2050	Inspiration for developments in Luxembourg for the Rhine Basin.
The Netherlands	Ranges between SSP5-8.5 (upper bound) and SSP1-2.6 (lower bound).	Deltascenarios2024 based on insights from KNMI (KNMI'23), PBL, WUR and Deltares describe four storylines ('Vlug', 'Stoom', 'Ruim' and 'Warm') that contain different combinations of climate change, emission reductions and socio-economic developments.	2050, 2100	Describes quite detailed already for water-related themes how these will change in the different scenarios and by what amount.
		WLO'24 scenario's (Prosperity and the Living Environment scenarios). These describe four storylines that combine demographic/economic growth and international climate policy.	2030, 2050	The new ones (WLO'24) are in development but looking at the previous ones (WLO'15), the focus lies on projections in other sections, and less in the water sector. A further translation to water-related themes must be made.

3.2 Inventory new water demand and water availability data

In addition to above scenario information, an inventory of available datasets on the national and river basin level within the Rhine countries was made to improve the data repository of the CHR and update the Rhine Ribasim model. The results of the inventory are shown in Table 3. As shown in Table 3 and in Table 4, no inventory has been made for the Rhine basin countries Belgium, Italy and Liechtenstein, as they do not have active representatives in the ICPR and CHR. The share of their territory located within the basin is limited and consequently the RIBASIM Rhine model has limited data requirements for these countries, in comparison to the other countries.

Table 3: Inventory of new datasets within the Rhine countries, with a focus on national datasets

Country	Name of dataset	Description of the dataset	Reference/Link	Used for	
				RIBA-SIM update	Validation
<i>All Rhine Countries</i>					
Discharge data	Global Runoff Data Centre (GRDC-Station Catalogue)	Discharge data available at the local level of the discharge station. Differs per station, but often 1920-2020. Daily discharge.	Link Data	✓	
Discharge data, precipitation and evaporation data	ICPR (2024)	Study about comparison and evaluation of Rhine discharge timeseries from various projects in Rhine countries ("HCLIM study", based on AR4 and AR5 (4 th and 5 th IPCC assessment scenarios))	ICPR technical report Technical report no. 297; Link Report		✓
	Deltares Report: Climate scenarios for the discharge of the Rhine and Meuse	Implications of the KNMI'23 climate scenarios for the discharge of the Rhine and Meuse; Discharge time series based on KNMI'23 climate change scenarios (based on AR6 (6 th IPCC assessment scenarios and RACMO and wflow models)	Buitink et al. (2023); Link Report	✓	✓
Reservoir data	Global Reservoir and Dam Database (GRanD_v1.1)	Global dataset. Available at the level of the dam. Name of reservoir, river, dam length, height, area, capacity, depth, and average discharge.	Lehner et al. (2011); Link Website	✓	
	Hydro LAKES v1.0	Global dataset. Available at the level of the dam.	Messenger et al. (2016); Link Website	✓	
	UCLA Circa 2015	Global dataset. Available at the level of the dam.	Sheng et al., 2016 ; Link Website	✓	
	Global Dam Watch	Global dataset. Available at the level of the dam.	Link Website	✓	
Cooling water use per power plant	Deltares Report: Influence of cooling water of power stations on the water availability in the Rhine Basin	Type and amount of power generated, cooling water system, surface water use. Given per power plant in Rhine Basin that has a capacity higher than 20 MW and that uses surface water. Based on a global dataset.	Mes E. & B. van Vossen (2022); Link Report		
	FAO and AQUASTAT	Irrigation areas are available as well as irrigation water requirements per country.	Link Website Link Data		

Country	Name of dataset	Description of the dataset	Reference/Link	Used for	
				RIBA-SIM update	Validation
Water use for irrigated agriculture	Data sets generated with novel agricultural water demand module within the hydrological wflow framework for better water management practices Deltares	Adjusted the works of Wada et al. (2011) and Van der Krogt et al (2021) a novel computational approach is scripted in the wflow model software package as an agricultural water demand module. It facilitate the use of data sets like land use, GDP, crop type, sources of water supply and downscaling approaches to generate datasets of agricultural water use. Available at a resolution of 1km ² . A further update related to data input is on the way based on novel datasets in EU horizon STARS4Water (2025); see next item.	Wada et al.(2011); Van der Krogt et al (2021) Link Report	✓	
	Data Sets on Scenario Narratives. Horizon Europe project STARS4Water. Deliverable D2.5	Using the wflow computational water demand approach (see above) STARS4Water produced an update of the dataset based on recent global datasets on land use, GDP, etc. The generated water demand datasets are coherent among 7 STARS4Water river basin hubs, including the Rhine basin. The dataset represent water demand for the historical period and those for the near future (2031-2060) based on various SSPs. Available per country and/or (sub)basin. Available at a resolution of 1km ² . Based on data ranging from 1961-2014.	Link Report Piniewski et al. (2025); Link Dataset Link Model		✓
	Purnamasari et al. (2025)	STARS4Water also develops a novel framework that combines hydrological modelling and satellite observations of land surface temperature (LST) to assess irrigated water demand (PhD research). During the execution of this project intermediate results are used: new irrigation area map and collected observed water use data.	Link Website Link Report Link Paper 2025a Link Paper 2025b (in review)	✓	✓
Water use for industrial and domestic use	Datasets generated with novel industrial and domestic water demand module within the hydrological wflow framework for better water management practices Deltares	Adjusted the works of Wada et al. (2011), Lips (2020) and Van der Krogt et al (2021) a novel computational approach is scripted in the wflow model software package as a drinking and industrial water demand module. It facilitate the use of data sets like population, GDP, consumption and downscaling approaches to generate datasets of drinking and industrial water use (which includes cooling water for energy production). Available at a resolution of 1km ² . Based on data ranging from 1961-2014. A further update related to data input is on the way based on novel datasets in EU horizon STARS4Water (2025); see next item.	Wada et al.(2011); Krogt et al. (2021); Link Report	✓	
	Data Sets on Scenario Narratives. Horizon Europe project STARS4Water. Deliverable D2.5	Using the wflow computational water demand approach (see above) STARS4Water produced an update of the dataset based on recent global datasets on land use, GDP, etc. The generated water demand datasets are coherent among 7 STARS4Water river basin hubs, including the Rhine basin. The dataset represent water demand for the historical period and those for the near future (2031-2060) based on various SSPs. Available per country and/or (sub)basin. Available at a resolution of 1km ² . Based on data ranging from 1961-2014.	Link Report Piniewski et al. (2025); Link Dataset Link Model		✓

Country	Name of dataset	Description of the dataset	Reference/Link	Used for	
				RIBA-SIM update	Validation
Navigation flow threshold*	CCNR, STARS4Water	CCNR has information on 3 locations representative for inland navigation (reliability required minimum water depth related to economic impact). Three locations.	PowerPoint available through ICPR Low Water group.		
Growing seasonal flow threshold for e-flows*	STARS4Water	STARS4Water develops a novel framework for e-flow assessments based on statistical analyses (under development, including Rhine case). Available at locations Lobith, Köln, Kaub, Worms, Maxau and Basel. Based on information from 2011.	PowerPoint available through ICPR Low Water group.		
Water extraction points for agriculture	Source (SW/GW and river)	Indicates the source (SW/GW and which river), however, not the amount abstracted for it, solely for very few locations. For the current situation. On level of water extraction points for irrigation. For several countries in Europe, including the Rhine countries.	Data available via BAFU; Link Report		
Abstraction and diversion	ICPR water intake scheme	Inventory of location of abstractions along the Rhine river	Data available via ICPR secretariat		
Austria					
Current and future water demand	'Water Treasure of Austria' project	Water resource scenarios for the Grand Est region, split into 99 regions—Rhine-relevant: 51–54—and three sectors: drinking water, agriculture, and industry. Covers current and 2050 projections under both positive and negative scenarios. See Excel file for details.	Link Report Link Website Link Data Download		
Farm Structure Survey	'Farm Structure Survey' - Irrigable area .	Available per federal province (total of 9 federal provinces). Available for the years 2010, 2013, 2016, 2020. No water demand for irrigation is mentioned here. Is available in table format.	Link Website		
Climate change adaptation	Den Klimawandel für Österreichs Wasserwirtschaft (in English: Adaptation Strategies for Austria's Water Management)	Austria-wide water management study across 9 federal provinces, with data for 2010, 2013, 2016, and 2020. Focus on climate-driven changes affecting extremes (high/low water), water balance, quality, and use. Updated in 2018 for extremes. Projections for 2021–2050. Follow-up research is ongoing to refine and update findings, per Austrian representatives.	Link Website		
France					
Water abstractions	The National Database of Quantitative Water Abstractions of France (BNPE)	Surface and groundwater, location and category of water use. Yearly volumes ranging from 2008-2022.	Link Database		✓

Country	Name of dataset	Description of the dataset	Reference/Link	Used for	
				RIBA-SIM update	Validation
Current and future water availability	Source: Grand Est Biodiversity Platform – quantitative assessments and future action	Water resource projections for the Grand Est region (mid-2000s to 2100), covering sectoral withdrawals (agriculture, industry, energy, domestic use), return flows, and infrastructure (dams, canals). Data is available by tributary (e.g., Upper Rhine) and in French.	Link Website and Reports		
	Source: Grand Est Biodiversity Platform – quantitative assessments and future action	Water resource projections for the Grand Est region (mid-2000s to 2100), covering sectoral withdrawals (agriculture, industry, energy, domestic use), return flows, and infrastructure (dams, canals). Data is available by tributary (e.g., Upper Rhine) and in French.	Link Website and Reports		
Germany					
Water availability for future and current situations	WADKlim using DESTATIS Data	Future and current situations, climate change effects, 'WADKlim' project: Water availability for current and future scenarios (up to 2070), influenced by climate change. Covers drinking water, irrigation, and industry. Demand projections vary by sector: drinking (3 population growth scenarios), industry (3 economic growth scenarios), and irrigation (agricultural area and crop changes). Spatial scale unspecified.	Umweltbundesamt (2024) Link Report		✓
Water supply and demand	Projected up to 2100, household, agriculture, industry, 'WatDEMAND' project	Water supply and demand projected up to 2100 for household, agriculture and industry. 'WatDEMAND' project - Results are not available yet. At the level of districts and independent cities for household, agriculture and industry.	Report not available yet. Link Website		
Industrial water demand	Study by Paul Levin Degott	Industrial water demand through study by Paul Degott. Industrial water withdrawal at Bundesland (federal state) level, split in surface water, imported and groundwater and split to subsectors within industry (E.g. paper, chemicals etc.). Current. Based on data from 2019 or 2013-2021.	Degott L., Paul (2023) Ppt and MSc Thesis available via ICPR.		✓
Reservoir volumes	General broad information, Talsperren in Deutschland	For several German reservoirs. German dataset. Available at the level of the dam in Germany. Based on studies taken place in 1998 and 2007.	PowerPoint available via ICPR. Link Website	✓	
Cooling water demand	General broad information, water availability for cooling needs in electricity production sector	At locations Lobith, Köln, Kaub, Worms, Maxau and Basel.	Based on information from 2011.		
<u>Water availability for cooling (Energy)</u>	A European study on future changes of freshwater needs in the	Europe-wide study (5 arc-minute grid) on future freshwater needs for electricity production, focusing on cooling water availability. Based on two SCENES scenarios (Fortress Europe, Sustainability Eventually) combined with IPCC SRES A2 and B1 climate projections. Covers	Flörke et. al () Link Report		

Country	Name of dataset	Description of the dataset	Reference/Link	Used for	
				RIBA-SIM update	Validation
	electricity production sector:	seasonal water availability changes up to 2050. Includes data for Garzweiler and Harnbach mines (2022).			
Water use for filling mines	General broad information	For two mines which are Garzweiler and Harnbach. Based on information from 2022.	Powerpoint available via ICPR and personal email correspondences.		
Discharges	Climate change induced discharge scenarios for the Rhine basin (HCLIM).	The HCLIM study, conducted by the ICPR Expert Group on Climate (EG HCLIM), updates Rhine discharge scenarios using daily flow simulations from Switzerland, Germany, France, and the Netherlands. Results are published in ICPR Report No. 297, detailing data sources, processing, and indicators. Due to ICPR's lack of a data system, the CHR hosts the datasets and figures online.	ICPR (2024) Link Report		✓
Industrial water use	Master Thesis (DESTATIS data)	Collection and analyses of DESTATIS datasets to estimate the industrial water use in the Rhine catchment.	Degott L., Paul (2023)		✓
Industrial water supply	Klimawandel: Wasser knapp – Industrie hat jahrzehntelange Entnahmerechte (CORRECTIV)	CORRECTIV's investigation shows that major industries in Germany hold long-term water extraction rights, potentially threatening public supply as climate change worsens. The data reveals top industrial water users by state.	Joeres, A., Huth, K., & Steeger, G. (2022) Link Website		✓
	Klimawandel: Wasser knapp – Industrie hat jahrzehntelange Entnahmerechte (CORRECTIV)	CORRECTIV's investigation shows that major industries in Germany hold long-term water extraction rights, potentially threatening public supply as climate change worsens. The data reveals top industrial water users by state.	Joeres, A., Huth, K., & Steeger, G. (2022) Link Website		✓
Luxembourg					
Reservoir area and volume	Data on the EschSurSure reservoir provided by La gestion de l'eau	It gives for a certain area, the volume and inflow at a height increase of 1 cm for the reservoir EschSurSure.	Excels not publicly available. Shared with Deltares.	*	
Reservoir level and amount of electricity generated	Data on the EschSurSure reservoir provided by La gestion de l'eau	It gives for a certain water level the amount of electricity in kW generated for the reservoir EschSurSure.	Excels not publicly available. Shared with Deltares. , Not used because provided later than update ,	*	

Country	Name of dataset	Description of the dataset	Reference/Link	Used for	
				RIBA-SIM update	Validation
	Data on the EschSurSure reservoir provided by La gestion de l'eau	It gives for a certain water level the amount of electricity in kW generated for the reservoir EschSurSure.	Excels not publicly available. Shared with Deltares. Not used because provided later than update ,	*	
<i>The Netherlands</i>					
Groundwater and surface water availability an flows, water demand	Dutch Delta Programme, Landelijk Hydrologisch Model	Dutch Delta Programme data on groundwater and surface water availability, distribution, supply, and demand (for flushing, level control, drinking, industrial, and agricultural use), based on the Landelijk Hydrologisch Model (LHM). Available for both regional and main surface water systems as well as groundwater, up till 250x250 m ² grid, aggregated into 17 subregions or 5 main regions. Covers current, 2050, and 2100 scenarios.	Link Website Link Data	✓	
<i>Switzerland</i>					
Drinking water use	Drinking water use	Schweizerischer Verband für Wasser, Gas und Wärme The drinking water demand data is available per extraction location in yearly values. Per extraction location in Switzerland. Yearly values.	Can be derived from SVGW via: wasser[at]svgw.ch		✓
Water levels and discharge volumes from lakes, rivers, and groundwater	Lakes, rivers, groundwater (report format)	Water levels and discharge volumes from lakes, rivers and groundwater. However, available only in report format and small station level, no real data which we can use. For the Rhine, information is given on the Rhein – Diepoldsau; Rhein – Basel and several tributaries. Books per year available from 1996-2021.	Link Report		
Water demand for agriculture	Currently being estimated	Water demand for agriculture. This is currently being estimated. Current situation and climate change scenarios until 2050. National level, not local analysis.	Available via annelie.holzkaemper[at]lagroscope.admin.ch		
Current and future water availability	Hydro-CH2018, 207 catchments, six different sectors	On level of 307 medium-sized Swiss catchments. Information given for six categories: drinking water, industry, artificial snow, agriculture, ecology and hydropower. For the current time (1981-2010) and future conditions represented by three climate model chains RCP2.6; RCP4.5; and RCP8.5. Shapefiles and Excel files.	Link Report Link Paper Link Dataset		
Dams and reservoir data	Swiss dams, table format and map	Data available per dam location.	Swiss Committee on Dams, 2024. Link Dataset.	✓	

Country	Name of dataset	Description of the dataset	Reference/Link	Used for	
				RIBA-SIM update	Validation
Socio-economic scenarios	NCCS-Impacts program: Sozioökonomische Szenarien für die Schweiz (2024):	Socio-economic scenarios for Switzerland to model land-use and CO2 emissions through NCCS-Impacts program. Research is taking place, but results are solely available from end 2025 or later. Multiple socio-economic pathways (SSP-CH) based on global SSPs	BAFU Link Website		
* Not used because provided later than update					

3.3 Gaps in datasets to improve the existing databases and IWRM Rhine modelling framework

The inventory of national datasets demonstrates that data is readily available for data analyses and modelling. However, data is also very diverse among the countries: how it is collected in the field, generated by models, handled, accessibility, reusability, etc. For example, water demand is closely monitored in one country and modelled in another for making assessments. Several datasets are under development in ongoing projects or will be published soon. Some datasets are hard to find, for example, data on the hydrological requirements of ecosystems or environmental flows.

First reflections on data gaps per country that already arise - from a Ribasim modelling perspective and based on the bilateral meetings with the ICPR representatives – is presented in Table 4. The data inventory and the data gaps presented in this table may form the starting point for further, more detailed data collection/data development and defining publication procedures within the involved organizations (e.g. CHR, ICPR and CCNR).

Table 4 is answering question 4 from the CHR: 'What local datasets are required to improve the CHR existing databases and modelling tools to describe the present situation?' Several data gaps are high on the data collection list for modelling purposes:

- Data regarding water storage, especially surface water reservoirs: reservoirs characteristics (area-volume-water level relations, etc.) and reservoir operational management (target release, etc.)
- Data regarding significant water abstraction or supply in current practice (location, discharge capacity, for what purpose, permits for water utilities and industries, etc.)
- Data on sources of water supply per water user: river, lake, groundwater, mixed, etc.

Table 4: First reflections on identification of data gaps per country (from a Ribasim modelling perspective) based on bilateral meetings with country representatives

Available data	Data gaps
Austria	
There is water demand data required in the Ribasim Rhine model for Austria, although this is for a very small area. This data is available for different regions and sectors, for different scenarios, now and in 2050.	No water demand data is available for a longer-term perspective (2100) and on a daily level. This dataset is also entirely not available yet but will become so likely later in 2024.
	For Austria, solely a very small part of the country is part of the Rhine Basin. In the Ribasim Rhine model; no reservoirs or natural lakes are included for Austria. It would be good, however, to be able to check whether large reservoirs or natural lakes are present and could be included to improve the model. Natural lakes and reservoirs and specific data on these, such as the level-surface area-volume relation is lacking on a national level. It has been suggested to collect this data through local efforts.
France	
Water abstraction data for different sectors is available for future water use (2050-2100) for the Grand-Est region. France has detailed data on water abstractions per year ranging from 2008-2022 per water user.	The current water abstractions per year ranging from 2008-2022 per water user are only publicly available on a yearly level, making daily water abstraction input not possible.
	There is still data lacking on the natural lakes and reservoirs in France, as level-surface area-volume relations and other input data relating to these two parameters is lacking on a specified national level.
Germany	
Water availability (supply and demand) data for future (2100) and current situation is obtained through DESTATIS, WADKLIM and WatDEMAND. This is on a district or city level for the different sectors.	These data sets are, however, not yet available for re-use in other research projects. Spatial and temporal level of detail? Time horizon? Future scenarios are based on national scenarios for Germany.
Solely very general information on reservoirs is publicly available, such as information on the volumes of the largest reservoirs.	Other data, such as the water level-surface area-volume relation or operational management, is still lacking.
Luxembourg	
In 2016, a national study on drinking water consumption in Luxembourg was conducted.	However, this study did not differentiate between sectors and was later found to have overestimated consumption, with 2021 figures showing 128,000 m ³ /day. For a recent project aimed at treating drinking water from the Moselle, projections from the 2016 study were adjusted, maintaining a constant distribution among household, industrial, and agricultural sectors.
SSP Scenarios for Luxembourg	An exchange with the national statistics authority (STATEC) was held regarding the national scenarios for Luxembourg. According to STATEC, the Shared Socioeconomic Pathways (SSP) underestimate Luxembourg's development.

Available data	Data gaps
Unpublished figures on Luxembourg's development up to 2070 were provided, along with a corresponding presentation. The annual data is continuous and can be used up to the required time horizon of 2050, with measured data available for the period 2015-2023.	Updated figures will be published by the end of the year, but these will only show slight differences up to 2050, with more significant changes expected between 2050 and 2070.
Luxembourg developed four different Scenarios. The four scenarios used are based on the relationship between the investment rate and technical progress. All scenarios are equally plausible, but scenario 4 is more likely and aligns with scenario 3. Scenario 4 is a more conservative scenario, featuring strong growth and high emissions despite the need for savings. Additionally it was noted that Luxembourg's current scenarios do not account for growth limitations, such as the availability of water resources.	Luxembourg is open to receive and answer more questions on this.
If energy data is still needed, this can also be provided by the national statistics authority (STATEC)	
The Netherlands	
For the Netherlands, solely reservoir data needs to be imported for the IJsselmeer, which is available.	
Water demand data for level control, flushing, irrigation, drinking water and industrial water is available for the current situation and on a daily level.	Future water demand for level control, flushing and irrigation is also available both for the future situation but according to the Dutch Delta Scenarios (based on KNMI'14 scenarios and KNMI'23 scenarios (published in 2025)).
Switzerland	
Dams, reservoir and natural lake data is in more detail available compared to other countries, such as type of dam, volume, area of reservoir, spillway capacity etc.	For the reservoirs and natural lakes, there is still difficulty to obtain certain required data, such as water level-area-volume relations
Drinking water demand data is available per extraction location in yearly values.	Local and specific data on industrial and agricultural water demand is lacking. Difficulty for industry is that big companies pump water from groundwater. Difficulty for irrigation is in uncertainty how much agriculture area and crops will change in the future. Also, both national level, local data is unavailable
There is data available on the current and future water demand and supply on medium-sized catchment level split up to industry, agriculture, ecology, hydropower, drinking water, and artificial snow production.	In 2025/2026, data on SES for Switzerland based on Suisse scenarios will be made available, however, not yet translated into impact on water availability and demand.

4 Co-designing transboundary scenarios for the Rhine River basin

This chapter introduces a first set of integrated narratives at the transboundary Rhine river basin scale, focussing on describing plausible future socio-economic aspects but considering climate change impacts as well. The narratives are plausible future pathways that outline the range of expected socio-economic changes under climate change. They are developed to support further studies on balancing water availability, water demand, and water allocation across subbasins of the Rhine River. The narratives are input to simulate and assess the potential impact on the Rhine River discharge in 2050, contributing to joint informed decision-making on future developments and climate adaptation in the basin.

Before describing the co-design of the socio-economic narratives and quantified information (together defined as: scenarios), we describe the KNMI'23 climate change scenarios first as they set the hydrological boundary conditions in this study.

4.1 Climate change futures for the Rhine basin as boundary conditions

In contrary to the socio-economic scenarios, a set of state-of-the-art climate change scenarios dedicated to the transboundary Rhine River basin are already available, including quantified information (KNMI, 2023; Buitink, 2023). These will be used as the starting point or boundary condition for designing the socio-economic scenarios in this SES project (2023-2025).

The KNMI'23 climate scenarios are climate projections developed by the Royal Netherlands Meteorological Institute (KNMI) and published in October 2023. They are generated with their own regional climate model RACMO and reflect the latest scientific knowledge from the IPCC's 2021 report (AR6) and CMIP6 climate models. As such, they are a follow-up of climate change projections (based on AR4 and AR5) published in the ICPR report of the HCLIM group in 2024 (ICPR, 2024).

The KNMI'23 climate scenarios outline four possible future climate pathways for the Netherlands, based on different combinations of greenhouse gas emissions and changes in temperature and precipitation. These scenarios are designed to help policymakers, researchers, and planners anticipate and prepare for the impacts of climate change. While tailored to Dutch conditions, they are grounded in global climate models and incorporate regional dynamics, making them relevant for assessing climate-related risks in upstream areas of the Rhine River basin and supporting transboundary water planning.

Here's a brief overview of the four KNMI'23 scenarios (van der Wiel et al, 2024):

- Hd: High emissions, dry scenario, SSP5-8.5, dry-trending — slightly wetter winters, substantially drier summers, ~4.9 °C warming by 2100 (selected for this study)
- Hn: High emissions, wet scenario, SSP5-8.5, wet-trending — substantially wetter winters, slightly drier summers, ~4.9 °C warming by 2100
- Ld: Low emissions, dry scenario, SSP1-2.6, dry-trending — slightly wetter winters, substantially drier summers, ~1.7 °C warming by 2100 (selected for this study)
- Ln: Low emissions, wet scenario, SSP1-2.6, wet-trending — substantially wetter winters, slightly drier summers, ~1.7 °C warming by 2100

KNMI'23 scenarios include two additional scenarios with moderate emission scenarios filling the gap between the high (SSP5-8.5) and low (SSP1-2.6) pathways:

- Md: Moderate emissions, SSP2-4.5, dry-trending — slightly wetter winters, substantially drier summers, ~2.4 °C warming by 2100 (selected for this study)
- Mn: Moderate emissions, SSP2-4.5, wet-trending — substantially wetter winters, slightly drier summers, ~2.4 °C warming by 2100

KNMI'23 provides data for the years 2033, 2050, 2100, and 2150, with some projections extending to 2300 for sea level rise. The scenarios cover climate conditions averaged over 30-year periods around these dates. They include detailed projects for the Rhine river catchments. Hydrologists at Deltares have translated these climate projections into projections of discharges. For more information on the climate change and hydrological scenarios, see Buitink et al, 2023, and the current the CHR Rheinblick2027 study (Wechsler, T. et al, 2025).

In this project we chose to take forward the three dry climate scenarios: *Ld*, *Md* and *Hd* scenarios for year 2050. For each scenario three timeseries of 30 hydrological years are available and we concatenate them to a 90 hydrological years timeseries available for each scenario. The scenarios describe how the climate could evolve in terms of temperature, precipitation, sea level rise, and extreme weather events, with a focus on drier summers. These three plausible climate future pathways are combined with co-designed plausible socio-economic futures across the Rhine River basin in 2050.

4.2 Three different plausible socio-economic futures for the Rhine basin

Three future socio-economic scenarios were co-designed for the Rhine basin, narrating different plausible futures:

- *Rhine Sustainable Community*
- *Rhine Middle of the Road*
- *Rhine Economic Growth*

Each scenario provides a unique perspective on an uncertain socio-economic future and how to navigate the complexities of drought risk management in a changing climate. Figure 7 shows the key differences between the scenarios and their similarities. The *Rhine Sustainable Community Scenario* focuses on the energy transition, local economies, and environmental protection, while the *Rhine Economic Growth* scenario emphasises further intensification of agriculture, use of fossil fuels, and innovation in the global economy. The *Rhine Middle of the Road* scenario is in between the two.

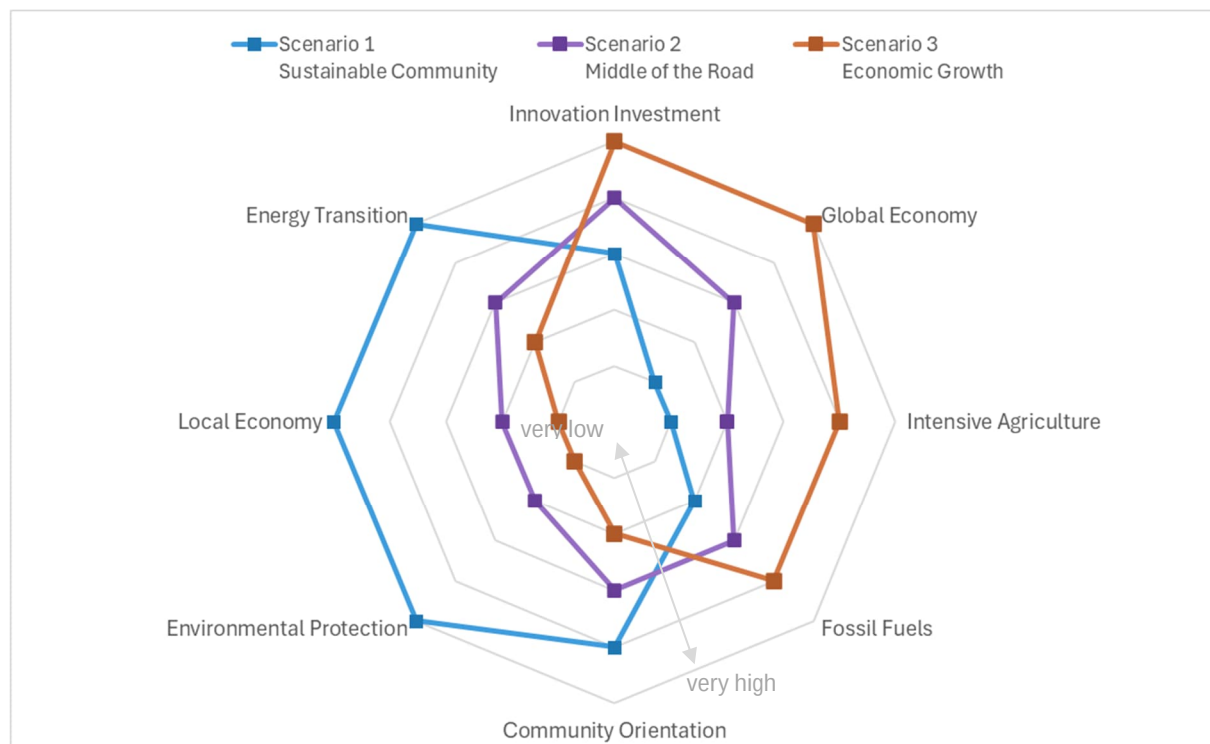


Figure 7: Key characteristics of different socio-economic scenarios for the Rhine river basin relative to each other. (Ranging from scoring very low (middle of the spider web) to very high (upper boundary of the spider web)).

Figure 7 shows a **qualitative** comparison between the scenarios and provides an impression of which characteristics the scenarios are similar, slightly different, or very different through a relative score for each scenario: ranging from very low to very high.

4.3 A brief description of *Rhine Sustainable Community*, *Rhine Middle of the Road* and *Rhine Economic growth* narratives

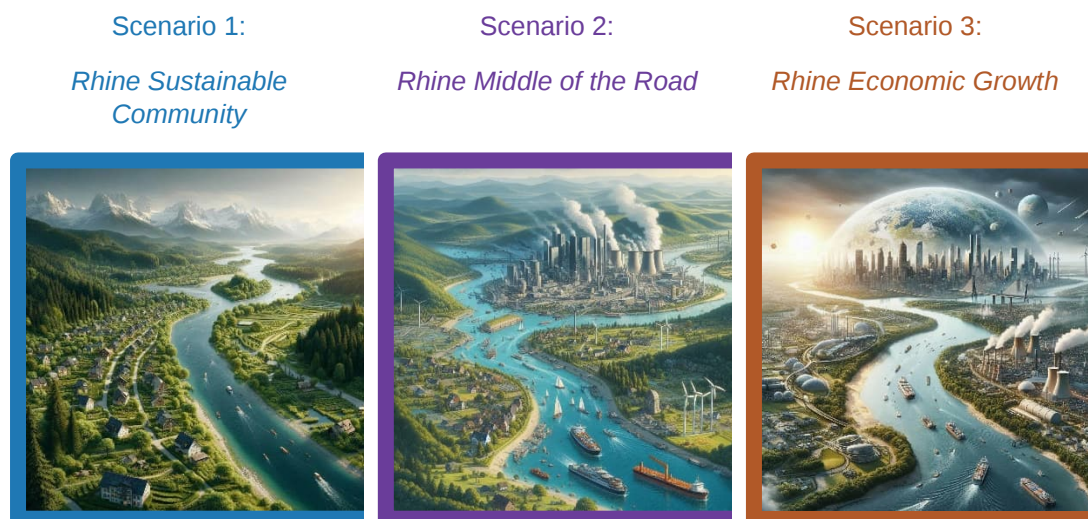


Figure 8: Interpretation of the future scenarios by AI - Generated with Copilot (16.09.2024)

In the “**Rhine Sustainable Community**” scenario, the focus is on environmental protection and the development of a sustainable society.

The narrative for this scenario envisions a world where green energy sources are the norm, and strong civil society plays a crucial role in driving cooperation and collective action particularly on a local level. Communities prioritize local and global environmental initiatives, leading to significant reductions in carbon emissions and the preservation of natural resources. The emphasis on sustainability fosters innovation in renewable energy technologies and promotes a circular economy on national levels, where waste is minimized, and resources are reused efficiently. This scenario highlights the importance of social cohesion and the active participation of citizens in creating a resilient and environmentally conscious society. For those who are familiar with IPCC scenarios, this scenario is inspired by SSP1 and RCP2.6 of the IPCC 6th report.

The “**Rhine Middle of the Road**” scenario depicts a world with moderate economic and population growth, where fossil fuels continue to play a significant role in the energy mix. The transition to renewable energy sources is slow, and while there are efforts to reduce carbon emissions, progress is gradual and often hindered by economic and political challenges. In the narrative for this scenario, societies balance economic development with environmental concerns, but the pace of change is not sufficient to address the most pressing issues. This scenario reflects a pragmatic approach, where incremental improvements are made, but the overall impact on sustainability is limited by the continued reliance on traditional energy sources and the slow adoption of green technologies. This scenario is inspired by SSP2 and RCP4.5 of the IPCC 6th report.

In the “**Economic Growth**” scenario, national security and economic growth are the primary drivers of policy and development. Intensive agriculture and industrial activities dominate the national economy, leading to significant advancements in technology and infrastructure. However, this rapid growth comes at the expense of environmental sustainability, as natural resources are heavily exploited to meet the demands of a growing population and expanding industries. The focus on national interests and economic competitiveness often leads to conflicts over resources and environmental degradation. While technological innovations may offer some solutions, the overall impact on the environment is negative, and this growth model is less sustainable on the long-term. This scenario underscores the tension between economic ambitions and the need for sustainable development. This scenario is inspired by SSP5 and RCP8.5 of the IPCC 6th report.

More detailed qualitative overview

Based on these three lines of reasoning more concrete narratives were developed in combination with different biophysical environments and climate change impacts and varying socio-economic drivers. Both were then described in their impacts on water users in the Rhine basin. Table 5 shows a qualitative overview of the three narratives for the Rhine basin. Quantifications are presented in the subchapter thereafter. A detailed description of the different aspects under each scenario is provided in Annex A.

Table 5: Overview of the co-designed scenario narratives for the transboundary Rhine River basin

NO	ASPECTS	SCENARIO 1: RHINE SUSTAINABLE COMMUNITY	SCENARIO 2: RHINE MIDDLE OF THE ROAD	SCENARIO 3: RHINE ECONOMIC GROWTH
	Key Characteristics	Environmental protection, sustainable society, green energy, strong civil society, cooperation	Moderate economic and population growth, fossil fuels, slow energy transition	Global economic growth, intensive agriculture
BIOPHYSICAL ENVIRONMENT				
1	Emissions scenario	Emissions decrease rapidly; global warming in 2100 will reach 1.7°C	Emissions gradually decrease after an initial increase; global warming in 2100 will reach 2.8°C	Emissions increase steadily; global warming in 2100 will reach almost 5°C
2	Accompanying climate change	Low climate change impact	Medium climate change impact	High climate change impact
3	Global Climate scenario	RCP 2.6	RCP 4.5	RCP 8.5
4	Rhine discharges	KNMI'23 Ld Scenario ~1.7°C ~0.45 m (SLR 2100)	KNMI'23 Md Scenario ~2.4°C ~0.65 m (SLR 2100)	KNMI'23 Hd Scenario ~4.9°C ~1.20 m (SLR 2100)
5	Natural Environment	Environmental needs and boundaries are respected. Declining Influx of micropollutants Reduction of fish migration obstacles: Minimum flow requirement habitat connection	Biodiversity and forests under pressure, but environmental needs and boundaries are considered. Water quality is threatened Prolonged low flow periods Ecosystem health is declining Hydrological patterns become more extreme	Similar to Middle of the road scenario, but no rules for minimum flow requirement for the natural environment.
SOCIO-ECONOMIC DEVELOPMENTS				
1	Population growth	Average growth in Rhine countries: 8% (SSP 1)* 61 million in the Rhine Basin (same as current)	Average growth in Rhine countries: 7% (SSP 2) 62 million in the Rhine Basin	Average growth in Rhine countries: 17% (SSP 5) 65 million in the Rhine Basin
2	Urbanization	Slight increase in population in cities like Cologne, Frankfurt, Rotterdam, Stuttgart, Dusseldorf. Average rate in Rhine countries: 10% (SSP 1)	Average rate in Rhine countries: 9% (SSP 2) Moderate increase in population in cities like Cologne, Frankfurt, Rotterdam, Stuttgart, Dusseldorf. Average rate in Rhine countries: 9% (SSP 2)	Average rate in Rhine countries: 10% (SSP 5) Significant increase in population in cities like Cologne, Frankfurt, Rotterdam, Stuttgart, Dusseldorf. Average rate in Rhine countries: 10% (SSP 5)
3	Economic growth	Average GDP per year 1,93% (SSP 1) Slight growth in GDP	Average GDP per year 1,67% (SSP 2) Moderate growth in GDP	Average GDP per year 2,78% (SSP 5) Highest growth in GDP
4	Economic sectors	Small growth in industrial sectors Growth in sustainable local Recreation and Tourism	Free trade and stable markets support the growth of major economic sectors, with cities becoming technological hubs	Flourishing economic industrial sectors Growth in large scale tourism with focus on luxury and comfort

NO	ASPECTS	SCENARIO 1: RHINE SUSTAINABLE COMMUNITY	SCENARIO 2: RHINE MIDDLE OF THE ROAD	SCENARIO 3: RHINE ECONOMIC GROWTH
			Growth in recreation and tourism along the Rhine from all over Europe	
5	Technology and innovation	Strong investment in education and technologies, especially efficiency technology	Technological advancements increase water efficiency, though no major breakthroughs	High Investment in technologies
6	Resource and Energy	Fast transition to more renewable energy and less mining	Efforts to reduce resource and energy consumption continue, with a slow increase in the share of renewable energy.	Slow transition to more renewable energy and less mining
7	SDG's and EU Green Deal	Increasing commitment to achieving development goals. Green Deal aspects are integrated, at accelerated pace: Investment in Clean Technologies, Carbon Pricing Mechanisms etc.	Policies like the SDGs and EU Green Deal promote ecological restoration and sustainable water management, though implementation is gradual.	Slow commitment to achieving development goals and significant environmental degradation Lack of environmental concern. Delayed integration of Green Deal aspects
8	Cooperation and decision making	Strong regional cooperation, focus on community engagement and local economy Local, sub-basin, regional, community oriented	Cooperation between governments focuses on harmonizing water resilience interests, flood risk management, and water quality management in the Rhine basin. National and EU oriented	Competitive global markets, strong Rhine riparian countries collaborative action between governments and private sector with focus on global market guided by EU regulation National, EU and private sector oriented
IMPACTED WATER RELATED SECTORS				
1	Water supply - Agriculture	Extensive agriculture Slight increase in water use for irrigation	Intensive agriculture Strong increase in water use for irrigation	Very intensive agriculture Extensive increase in water use for irrigation
2	Drinking water	Groundwater remains an important source for drinking water	Groundwater and regional surface water become primary source for drinking water	Groundwater sources are depleted and drinking water sources shift to surface water on a larger scale
3	Industrial water & Cooling water	Decreased cooling water use	Power plants, optimized cooling water usage, technical advancements, additional water resources	Increased cooling water use but also more efficiency, due to investment in technological advancements
4	Inland water transport	More containers and emission free transport.	Inland waterway transport, adapted, climate change impacts, adjustments to infrastructure. Maintaining agreed min. low water discharges conditions.	More bulk transport requiring higher minimal depth for navigation than other scenarios.
5	Hydropower	No new hydropower stations Switzerland will likely build new ones, also in this scenario	Hydropower generation, low-flow periods, environmental considerations, influencing hydropower practices	Opening of new hydropower stations

NO	ASPECTS	SCENARIO 1: RHINE SUSTAINABLE COMMUNITY	SCENARIO 2: RHINE MIDDLE OF THE ROAD	SCENARIO 3: RHINE ECONOMIC GROWTH
6	Mining	Filling of the mines starts in 2030 and takes 40 years.	Filling of the mines starts in 2030 and takes 40 years.	Mines remain open and still active.
7	Water level management and flushing (specific for the low-lying part of the Netherlands)	Increased flushing required for wetting peatland to minimize CO2 emissions.	Increased flushing required due to compensating impact of saltwater intrusion due to moderate sea level rise, maintain dike safety and for wetting peatland to minimize CO2 emissions.	Increased flushing required due to compensating the impact of saltwater intrusion due to high sea level rise, maintain dike safety and for wetting peatland to minimize CO2 emissions.

4.4 Translating narratives into quantified information for modelling purposes

To arrive at socio-economic scenarios the narratives are translated into quantified information that can be used as model input by adapting the industrial, domestic, and irrigation water demand data and the irrigated areas data for each subbasin for the reference situation. This is done by using the fractions displayed in Table 6. The timeseries on domestic, industrial and irrigation water demand and irrigated area for each subbasin are multiplied by using the fractions, generating the new timeseries for each socio-economic scenario (see also paragraph 5.2.3). Which country percentage is used for which subbasin specifically is displayed in Table 6, determined based on which country the subbasin overlaps with most.

Table 6: Translating scenario narratives for 2050 situation into factors of change to the present situation

Modelled Sectors in IWRM Rhine modelling framework			Modelled Scenarios in IWRM Rhine modelling framework																	
			Scenario 1 – Sustainable Community						Scenario 2 – Middle of the road						Scenario 3 – Global Growth					
			AT	FR	DE	LU	NL	CH	AT	FR	DE	LU	NL	CH	AT	FR	DE	LU	NL	CH
			5	6	-2	22	3	13	4	6	-3	21	3	12	14	10	5	38	7	25
Population Growth (%)			16	5	11	7	7	11	12	5	11	7	7	11	16	5	11	7	7	11
Urbanisation (%)			2.1	2.2	1.7	1.9	2.1	1.6	1.8	1.8	1.3	1.8	1.9	1.4	3.0	2.9	2.5	2.8	3.0	2.5
GDP (average/year) (%)			-	+8	+4	-	+21	+4	-	+10	+5	-	+30	+10	-	+16	+8	-	+40	+15
Irrigation	Total irrigated area (% from total agr. area)	-	1.08	1.04	-	1.21	1.04	-	1.1	1.05	-	1.3	1.1	-	1.16	1.08	-	1.4	1.15	
	Total irrigated area (fraction)																			
	Change in water use for irrigation (%)	+20						+80						+150						
	Change in water use for irrigation (fraction)	1.2						1.8						2.5						
	Assumptions	Data from the SSP Scenarios presented in Table 15 (Annex) and summarized on top of this table on population growth and urbanization in combination with qualitative assumption of Table 5 were used to create the quantitative assumptions in this table. Numbers of change in irrigated area from the Deltas Scenarios (Van der Brugge et al., 2024). These have been calculated using the Dutch Regional scan agriculture tool (“Regioscan landbouw” (in English: Regional scan agriculture) (STOWA, 2018), and are expressed as percentage change.																		
	Industrial	Change in industrial and energy water demand (%)	-40						-10						+30					
		Change in industrial and energy water demand (fraction)	0.6	0.6	0.6	0.6	0.6	0.6	0.9	0.9	0.9	0.9	0.9	0.9	1.3	1.3	1.3	1.3	1.3	1.3
		Assumptions	Data from the SSP Scenarios presented in Table 15 (Annex) and summarized on top of this table on economic growth in combination with qualitative assumption of Table 5 were used to create the quantitative assumptions in this table. Assumed was a reduction of 20% of daily use in the sustainable scenario based on the reduction in drinking water combined with the expected future population.																	
	Domestic	Change in public water demand (%)	-5	-15	-20	-5	-20	-10	+5	+5	-5	+5	+5	+5	+20	+15	+10	+15	+15	+15
		Change in public water demand (fraction)	0.95	0.85	0.8	0.95	0.8	0.9	1.05	1.05	0.95	1.05	1.05	1.05	1.2	1.15	1.1	1.15	1.15	1.15
Assumptions		Data from the SSP Scenarios presented in Table 15 (Annex) and summarized on top of this table on GDP, population growth and urbanization and economic growth in combination with qualitative assumption of Table 5 were used to create the quantitative assumptions in this table.																		

5 Improvement of the IWRM Rhine Modelling Framework

In 2023, the CHR and ICPR expressed the need for an integrated water resources management (IWRM) modelling framework for the Rhine basin to explore scenarios. This must support integrated river basin management planning based on an IWRM approach. It will be used for strategic assessment of water resources availability, water allocation, use, and low flow strategies. This modelling framework should support informed decision-making and comply with EU Directives by enhancing understanding of the Rhine river basin's water resources system. It should incorporate and examine different regional climate and socio-economic scenarios for the Rhine, that the Rhine commissions CHR, ICPR, and CCNR wants to explore.

With support from the STARS4Water and the CHR, the modelling framework has been developed consisting of the Ribasim Rhine river basin and water allocation model coupled with the Wflow Rhine hydrological model. The Wflow Rhine model generates the datasets about the availability of water (natural river discharge timeseries) and water demand in the Rhine basin for the Ribasim Rhine model. Gridded datasets of the Wflow Rhine model are lumped to the subbasin level for the Ribasim Rhine model, representing the water availability and demand in each subbasin.

Important activities to arrive at the new IWRM Rhine Modelling Framework include:

- Migration of the Ribasim Rhine model (an integrated river basin management and water allocation model) that was created in 2021 (Van der Krogt et al., 2021) to the newest Ribasim model software package (version 8). (see: [RIBASIM](#)). The model was renamed to Ribasim Rhine model 2025.
- Updated network schematisation of the water resources system in nodes and links in Ribasim Rhine model 2025.
- Combining EU and global data with more regional to local data for better, localised model input, especially for modelling reservoirs in the Rhine basin.
- Connecting the Ribasim Rhine model to the Wflow Rhine model (a hydrological model) for integration of regional hydrological data and water demand data for domestic, industry, and agriculture sectors.

The approach and methodology enable assessment of availability of surface water, water use and allocation, and changes in reservoir storage and river flow due to climate change and water demand changes. The modelling framework provides the Rhine Commissions and other stakeholders with information on surface water availability, demand, use, shortages, and main Rhine river discharges.

5.1 New version of the Ribasim Rhine model

The first step in upgrading the Ribasim Rhine model was migrating to the latest software code (Ribasim 8 software code), benefiting from the new graphical user interface, database functionalities, and computational framework (Figure 9).

Additionally, the representation of the Rhine River system through the links and nodes network schematisation in the model itself was further detailed by, incorporating more knowledge about the functioning of the water system, particularly reservoirs, lakes, rivers, streams, and water users in sub-basins.

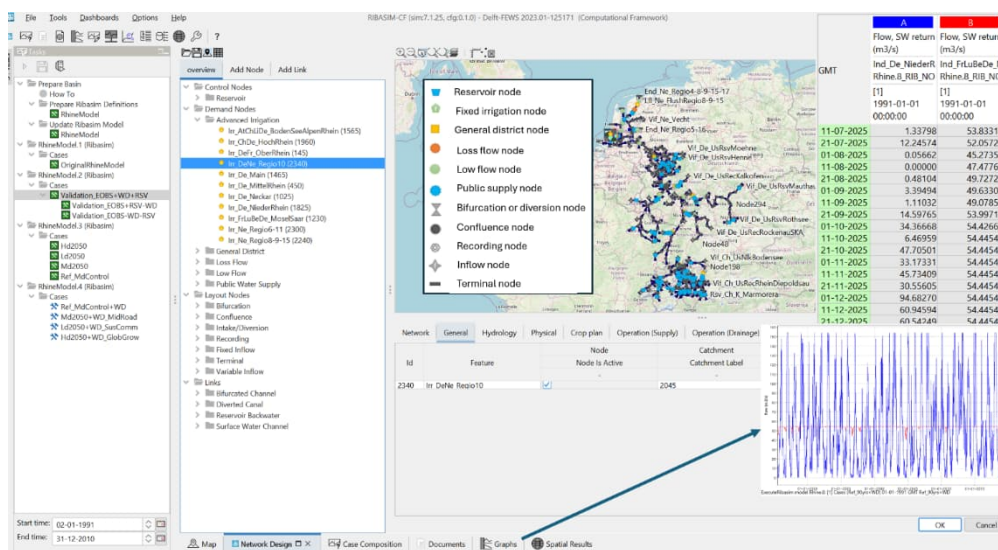


Figure 9: The Ribasim 8 graphical user interface showing the Rhine integrated river basin system network schematization

5.2 Update model data input describing the current and future situations

5.2.1 Reservoir and lakes

During the project, the model network schematisation in the Ribasim Rhine model was updated from 48 to 63 reservoirs and natural lakes, integrating more information about them. A new reservoir database was created by combining several global to local reservoir databases:

- HydroLAKES v1.0 (Messenger et al., 2016) (see: <https://www.hydrosheds.org/products/hydrolakes>),
- GRanD version 1.3 (Lehner et al., 2011): <https://www.globaldamwatch.org/grand/>
- UCLA Circa 2015 (Sheng et al., 2016) : (https://swotst.avisio.altimetry.fr/fileadmin/user_upload/SWOTST2018/Day2H_1415a_She_ngetal2018_ST_Montreal_LakeDB.pdf)
- Talsperren in Deutschland (Deutsches Talsperrenkomitee, 2013) <https://www.talsperrenkomitee.de/de/talsperren-in-deutschland.html>
- Global Dam Watch (GlobalDamWatch.org)
- SFEO (Swiss Committee on Dams, 2024) (<https://www.swissdams.ch/en/les-barrages/liste-des-barrages-suisse>)
- And some additional data provided by the ICPR secretariat, also in exchange with the BfG/BAW ongoing WWOptII project.

Only reservoirs containing a volume of 10 million m³ or more were included in the Ribasim Rhine model 2025, 63 reservoirs totally. Local datasets were used as much as possible for determining new volumes. When local dataset volumes were not available, volumes from other global datasets were used. Specific changes to the Ribasim Rhine model are displayed in Table 7. The database with reservoirs in the Rhine basin is open source. Consequently, the reservoir database was exchanged with the ICPR and ongoing WWOptII project of the BfG/BAW (Ebner von Eschenbach et al., 2025).

For many reservoirs, information about the water storage - water level - water area relationships as well as operational rules are not available. Instead, we made assumptions according to best expert knowledge and implemented those to be able to run the model.

Table 7: Overview of updates to the reservoir volumes in the Ribasim Rhine model 2025

Name of the reservoir node in the water network schematisation in Ribasim Rhine model (version 2025)	Volume in the previous Ribasim Rhine model (version 2021) (Mm3)	(Updated) volume in the new Ribasim Rhine model (version 2025) (Mm3)	Based on which dataset
Rsv_Ch_HK_LacdHogrín	84	53.2	Swiss Committee on Dams (2024)
Rsv_Ch_K_Curnera	41.1	41.1	Swiss Committee on Dams (2024)
Rsv_Ch_K_Gelmer	14	14	Swiss Committee on Dams (2024)
Rsv_Ch_K_Gigerwald	33.4	35.6	Swiss Committee on Dams (2024)
Rsv_Ch_K_Goescheneralp	76	76	Swiss Committee on Dams (2024)
Rsv_Ch_K_Grimsel (Spitallam)	101	101	Swiss Committee on Dams (2024)
Rsv_Ch_K_Kloental	56.4	56.4	Swiss Committee on Dams (2024)
Rsv_Ch_K_Limmern	93	93	Swiss Committee on Dams (2024)
Rsv_Ch_K_Lucendro	25	25	Swiss Committee on Dams (2024)
Rsv_Ch_K_Marmorera	62.6	62.6	Swiss Committee on Dams (2024)
Rsv_Ch_K_Nalps	45	45	Swiss Committee on Dams (2024)
Rsv_Ch_K_Oberaar	61	63.7	Swiss Committee on Dams (2024)
Rsv_Ch_K_Raterichsboden	27	27	Swiss Committee on Dams (2024)
Rsv_Ch_K_Rossens	220	220	Swiss Committee on Dams (2024)
Rsv_Ch_K_SantaMaria	67.3	67.3	Swiss Committee on Dams (2024)
Rsv_Ch_K_Schiffenen	65	65	Swiss Committee on Dams (2024)
Rsv_Ch_K_Schrah	150	150	Swiss Committee on Dams (2024)
Rsv_Ch_K_Sihlsee (Hünhermatt)	96.5	96.5	Swiss Committee on Dams (2024)
Rsv_Ch_K_Sufers	21.4	21.4	Swiss Committee on Dams (2024)
Rsv_Ch_K_ValleDiLei	200	200	Swiss Committee on Dams (2024)
Rsv_Ch_K_WohlenseeMuehleberg	1.6	25	Swiss Committee on Dams (2024)
Rsv_Ch_K_Zervreila	100.5	100.5	Swiss Committee on Dams (2024)
Rsv_De_HKE_Brombach	129	136.6	DTK (2013)

Name of the reservoir node in the water network schematisation in Ribasim Rhine model (version 2025)	Volume in the previous Ribasim Rhine model (version 2021) (Mm3)	(Updated) volume in the new Ribasim Rhine model (version 2025) (Mm3)	Based on which dataset
Rsv_De_HKSE_Wupper	25.9	25.9	DTK (2013)
Rsv_De_HSE_Bever	23.7	23.7	DTK (2013)
Rsv_De_K_Schluchsee	108	108	DTK (2013)
Rsv_De_KE_Rothsee	11.7	28.45	DTK (2013)
Rsv_De_T_Kerspe	15.5	15.5	DTK (2013)
Rsv_De_TH_Wahnbach	41.4	41.3	DTK (2013)
Rsv_De_TH_Wiehl	31.5	31.5	DTK (2013)
Rsv_De_THK_Agger	19.3	19.3	DTK (2013)
Rsv_De_THK_Mauthausl	21	20.7	DTK (2013)
Rsv_De_THKE_Bigge	171.7	171.7	DTK (2013)
Rsv_De_THKE_Henne	38.4	38.4	DTK (2013)
Rsv_De_THKE_Moehne	140.8	140.8	DTK (2013)
Rsv_De_THKE_Sorpe	70	70	Lehner et al., 2011; Messenger et al., 2016
Rsv_De_THS_GrosseDhunn	81	81	DTK (2013)
Rsv_De_THS_Obernhausen	14.9	14.8	DTK (2013)
Rsv_De_TK_Verse	32.8	32.8	DTK (2013)
Rsv_De_TKS_Ennepe	12.6	12.6	DTK (2013)
Rsv_Fr_TE_Madine	33	33	Lehner et al., 2011; Messenger et al., 2016
Rsv_Fr_TH_KruthWildenstein	12	12	Lehner et al., 2011; Messenger et al., 2016
Rsv_Fr_TK_VieuxPreLacDePierrePer	55	55	Lehner et al., 2011; Messenger et al., 2016
Rsv_Lu_TK_EschSurSure	62	62	Lehner et al., 2011; Messenger et al., 2016
Rsv_Ne_IJsselMarkerRandEemMeren	7000	7500	Lehner et al., 2011; Messenger et al., 2016

5.2.2 Natural river discharges, rainfall and evaporation

The availability of water simulated in the model is described by rainfall, evaporation and natural river discharges (i.e. runoff), both for the current and future situations under climate change. These are the “hydrological boundary timeseries” for water supply.

We used hydrological timeseries generated by the wflow Rhine Model in the KNMI'23 climate change project (Buitink et al., 2023) and include hydrological timeseries representing the reference (current) situation (based on historical, EOBS dataset):

- Synthetic hydrological timeseries (90 years hydrological time period timeseries) representing the reference (current) situation based on current climate statistics
- Synthetic hydrological timeseries (90 years hydrological time period timeseries) representing the situation in 2050 according to the new regional KNMI'23 climate scenarios for the Rhine basin (Van Dorland et al., 2024)

The Ribasim Rhine model was coupled with the Wflow Rhine model for smooth integration of the timeseries and to enable scenario runs.

To place the new natural river discharge series in a broader context, upon request of the ICPR an analysis and comparison has been conducted with climate change-induced discharge scenarios and values presented in ICPR Technical Report No. 297, prepared by the HCLIM Expert Group. The time series in the ICPR report are based on the 4th and 5th IPCC Assessment Reports (AR4 and AR5), whereas the newly developed series are derived from the latest 6th Assessment Report (AR6).

5.2.3 Water demand and use by domestic, industry and irrigated agriculture

The focus was on domestic, industry, and irrigated agriculture sectors to limit the amount of work undertaken. The domestic sector involves water use for essential household activities such as drinking, cooking, and cleaning. The industry sector relies on water for manufacturing, chemical production, cooling and energy generation (by powerplants; water for hydropower is not included in this study). The irrigated agriculture sector provides water to agriculture, ensuring crops receive adequate moisture to sustain productivity. Additionally, for the Netherlands, water use related to managing saltwater intrusion and maintaining water levels were included, which are crucial for ensuring dike safety, mitigating peat oxidation, and combating saltwater intrusion.

Since harmonizing and completing the collected datasets on current water demand was too ambitious for this project, we decided to update the water demand datasets for sub-basins using the new domestic, industrial and agricultural water demand modules in the Wflow. These modules simulate gridded water demand based on computational algorithms and global to EU datasets and country-specific information regarding population, GDP, population, etc., and assumptions for return flow fraction (non-consumed water). These modules are based on the same method that was used in the Ribasim Rhine model 2021. For details on these methods see the Volume 2 Annexes of the Ribasim River basin simulation model of the Rhine report (Van der Krogt et al, 2021).

In particular, we created the following datasets:

- Domestic water demand estimates are based on country-specific water withdrawal per capita, population data and taking into account seasonal temperature variation or differences between water demand in summer and winter.
- Industrial water demand estimates are based on (gridded) data on gross domestic product, electricity production, energy production, household consumption and population counts.
- Agricultural water demand estimates are based on meteorological conditions, type of crops, crop factors, land use, irrigated area and efficiency factor between gross and net irrigation.

The actual (reference) water demand for domestic, industry and irrigated agriculture was computed based on 30-year data from 2000 to 2030. Future water demand data is computed using actual water demand and quantitative assumptions based on the socio-economic narratives (see chapter 4).

Other model assumptions are:

- 35% of the water from the domestic water supply is consumed and the remaining 65% is collected and returns to surface water after treatment.
- For water for industry, the assumed percentage for consumption is significantly lower, namely 10%, and the remaining 90% returns to surface water.
- For irrigation, the assumption for return flow to surface water is 0%. Assumption for field efficiency (difference between gross and net demand) in agriculture is 80%. These factors are kept the same in each socio-economic scenario.

5.2.4 Water demand and use for maintaining water level and flushing

For the Delta-Rhine sub-basin, the water demand datasets were complemented by water demand datasets for flushing against saltwater intrusion and maintaining water levels, derived from the Dutch National Hydrological Instrument (nhi.nu).

Info: "Flushing polders and boezems" and "maintaining water levels in peat areas" refers to a water management practice in the Netherlands, specifically in the western and northern part of the country. A polder in the Netherlands is a low-lying tract of land that has been reclaimed from a body of water—such as a lake, river, or the sea—and is enclosed by dikes to form an artificial hydrological system. Water is intentionally flushed out of the polders into a "boezem" system. A "boezem" is a large body of water, such as a lake or canal, that acts as a reservoir for collecting excess water pumped from polders before it can be discharged into a major river or the sea by sluices or pumps. During periods of droughts "boezems" are also used as transport ways to bring water to the polders for maintaining water levels and reducing saltwater concentration levels.

Water enters low-lying polders through several pathways: infiltration and pressure from groundwater (including salt water intrusion, especially along the coast line), direct rainfall, and inflow from rivers and canals. This often leads to water surplus, which is managed by pumping or discharging through sluices during low tide. However, it is essential to maintain a balanced internal water level and good water quality. Excessive drainage or lack of water during dry periods can accelerate land subsidence, particularly in peat-based polders (former marshlands), where exposure to oxygen causes peat to decompose and the ground to sink. This has implications for dike and infrastructure stability, agricultural productivity, and climate resilience.

"Flushing rivers and lakes" involves introducing water from elsewhere, typically the main rivers Rhine (or its branches) and Meuse, to prevent external salt water intrusion (by surface water by open outlet (e.g. at Rotterdam) or by sea lock operation for ships (e.g. at IJmuiden). It also dilute and remove accumulated salts or pollutants within the water ways. The process helps maintain water quality especially during periods of low rainfall or high evaporation, or during low river flows (especially in combination with high storm surge levels at sea).

5.2.5 Water sources and priority list for supply

In the Ribasim Rhine model, water availability, supply, demand, use, and shortages are calculated per sub-basin and water sector to ensure effective resource management. The modelled water demand is linked with rivers (tributaries to the main Rhine river) in their sub-basin as sources for water supply.

Priorities are assigned to each sector to address specific needs. The domestic sector, involving essential household activities, is given the highest priority. The industry sector, relying on water for manufacturing, chemical production, energy generation, and cooling, is assigned the second priority. The irrigation sector, providing water for agriculture, is given the third priority.

These priorities help manage water resources effectively, ensuring essential needs are addressed first. Further research is required to gather more information on water allocation priorities among users in different countries. This information did not become available during this project. Hydrological requirements (such as ecological flows) are not taken into account in this study. However, increased low flow conditions and increased water consumption by economic sectors put pressures on the river ecosystems and riparian wetlands.

5.3 Outlook for further IWRM Rhine modelling framework updates

The Rhine River Basin Scenario Tool is a dynamic or a 'living' framework and requires ongoing maintenance and updates for effective water resources planning. In general, incorporating more quality data and details on the system's functioning will further improve the model's performance. Further updates on model schematisation and input data are possible, especially from national scenario studies and the CHR RheinBlick2027 study.

The framework can be extended further by linking with sectoral tools, such as those for agricultural assessment, inland shipping assessment or e-flow assessment. Some innovations are already underway, like a novel agricultural water demand and irrigation water use model based on satellite data and land surface temperature, developed in the STARS4Water project. An e-flow assessment tool is also work in progress and currently applied in an experiment with among others ICPR.

A major renewal of the Ribasim software is expected in the next one or two years, with state of the art water allocation modelling approaches. The new version also envisions a further seamless (in concept (calculation method, etc.) and timestep) integration with hydrological modelling (Wflow), reservoir management optimisation (RTC tools), and groundwater modelling (Modflow), accommodating a holistic Integrated Water Resources System simulation in high level of level.

Deltares envisions that the results of current ongoing research and developments, and/or dataset improvements will be included in the modelling tools in the event of future extensions of the SES project or similar initiatives, to strengthen the tool further.

The ICPR has expressed interest in being associated with or informed of the updates and innovations that will advance the IWRM Rhine Modelling Framework updates. The ICPR intends to continue work in the broader field of water availability and water demand/use (including projections) in the future. It would like to be associated with possible future CHR activities in this field, contribute with inputs and data, and benefit from the outcomes — for example, through the use of tools such as Ribasim and by incorporating the most up-to-date and accurate data available.

6 Scenarios assessment and analysis

This chapter presents the results of the assessment and analysis of transboundary socio-economic scenarios for the Rhine basin, based on model runs conducted using the *IWRM Rhine Modelling Framework*. The modelling outputs were interpreted in response to key questions raised by the ICPR, focusing on future water availability and demand, sector-specific shortages, and impacts on river flows under varying climate and socio-economic conditions.

These results are not intended as definitive conclusions, but rather as a foundation for informed stakeholder discussions. They represent a significant step forward within the SES research line of the CHR, and also for the ICPR and CCNR, in knowledge development toward understanding potential future challenges and trade-offs in water use and allocation, the plausible impacts on low river discharges, and support ongoing dialogue on adaptive strategies for transboundary water management.

6.1 Model runs for scenarios assessment

The new *IWRM Rhine Modelling Framework* evaluates three socio-economic (SE) scenario narratives (see Chapters 4.2 to 4.4) and three KNMI'23 climate change (CC) scenarios (KNMI, 2023; Deltares, 2023; see Chapter 4.1), based on the latest IPCC assessments.

Three future scenarios were developed by combining one SE narrative—co-designed with stakeholders—with one CC scenario from KNMI'23. These are assessed alongside a current reference scenario representing present-day climate and socio-economic conditions.

Table 8 provides an overview of the model runs applied in the Ribasim Rhine model for this scenario assessment. For consistency, the scenario names and associated colours shown in the table are used throughout the plots in this chapter.

Table 8: Overview of the reference and 3 scenarios, both for CC scenarios only and for the CC-SE combined scenarios. Colours are used in subsequent plots.

Scenario name or number	Climate change (CC) scenario		Socio-economic (SE) scenario narratives		CC-SE combined scenario
Reference	Current Climate (Reference)	+	Current Society	=	Current situation
1	Low CO2 mission Ld2050	+	Rhine Sustainable Community	=	Ld2050 + Sustainable Community
2	Moderate CO2 emission Md2050	+	Rhine Middle of the Road	=	Md2050 + Middle of the Road
3	High CO2 emission Hd2050	+	Rhine Economic Growth	=	Hd2050 + Economic Growth

6.1.1 Post-processing results: temporal resolution and spatial resolution

The Ribasim Rhine Model operates with a temporal resolution of 10 days (see Chapter 2), allowing for simulation of water demand, use, and shortages. Each climate scenario was run over 90 hydrological years, covering both the current situation and projected conditions for the 2050 time horizon. This long-term simulation period provides a robust basis for statistical analysis and for assessing variability and trends in water availability and allocation under different climate and socio-economic conditions (e.g., through box plots).

The assessment focused on nine distinct sub-basins and three key locations (see Table 9 and Figure 10) along the main Rhine River. The sub-basins were selected based on major geographical sections and tributaries of the Rhine basin, excluding the main stream of the Rhine itself.

Table 9: Rhine subbasins and locations Basel, Kaub and Lobith

No	Sub-Basin	Location 1	Location 2	Location 3
1	Alpine Rhine	Basel	Kaub	Lobith
2	High Rhine (incl. Aare)			
3	Upper Rhine			
4	Neckar			
5	Main			
6	Middle Rhine			Lobith
7	Lower Rhine			
8	Mosel/Saar			
9	Delta Rhine			

For the main Rhine River, three representative locations were selected to reflect upstream, midstream, and downstream conditions: Basel, Kaub, and Lobith. These sites were chosen for their strategic positions within the basin and their relevance to flow dynamics and water stress patterns. Specifically, sub-basins 1–3 contribute to flows at Basel, 1–5 at Kaub, and 1–8 at Lobith. The Delta Rhine was analysed separately due to its distinct hydrological characteristics.

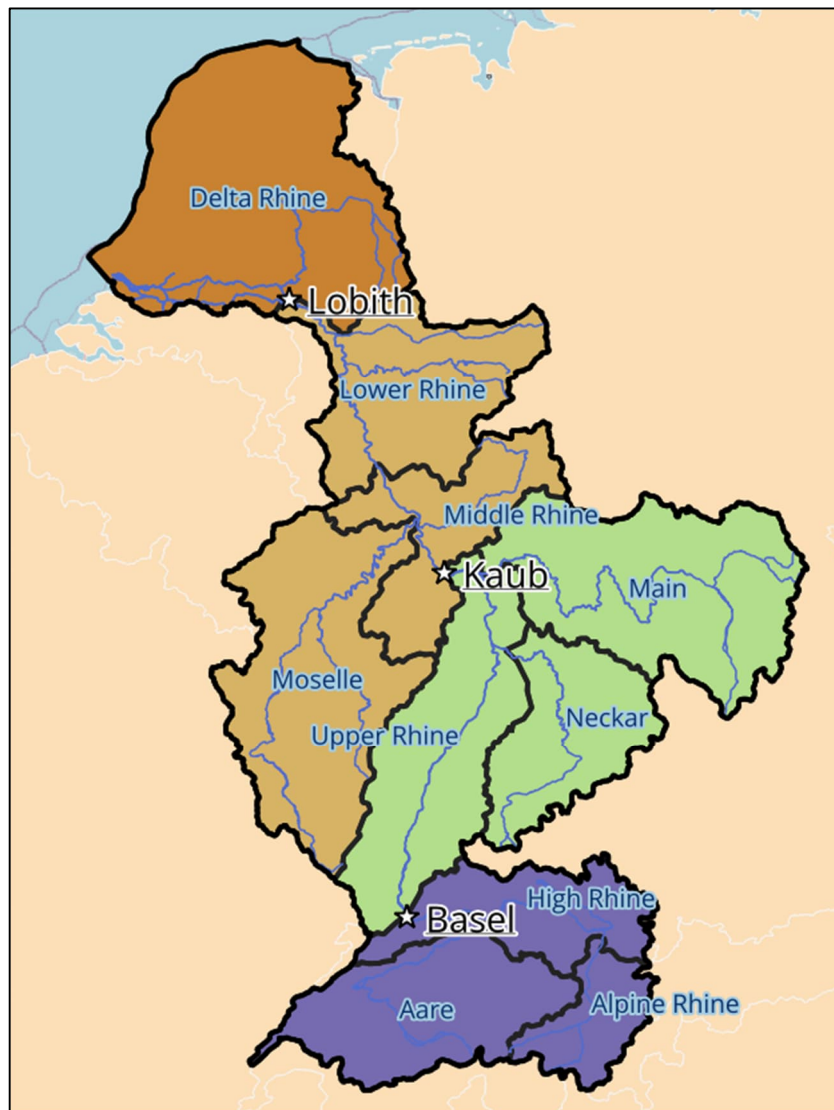


Figure 10: Rhine subbasins and key locations

6.1.2 EG LW Questions guiding the impact assessment of scenarios

The knowledge questions of the ICPR Expert Group on Low Water (EG LW) were guiding the analysis of the modelling results (Table 10). The analyses for the different items are presented in next subchapters.

Table 10: Overview of the questions of the Expert Group Low Water

EG LW Questions		Water availability	Use and demand	Scarcity and shortage	Impact on low flow
1	How much water is available in the Rhine basin area and how will this change in the future under climate change? (LW Q1)	X			
2	How are water resources used and for what purposes? (LW Q2)		X		
3	How will the demands on water resources develop in the future, in particular the agricultural water demand? (LW Q3)		X		
4	Which parts of the Rhine basin area will be affected by water scarcity risks in 2050? (LW Q5)			X	
5	What is the impact of growing water demand under climate change on the Rhine river low flows? (LW Q4)				X
		Chapter 6.2	Chapter 6.3	Chapter 6.4	Chapter 6.5

6.2 Water availability

6.2.1 Water availability in the Rhine basin

Natural water availability (e.g rainfall, runoff) was assessed per sub-basin. These are the hydrological input to the water balances (or so called “inflows” in the Rhine Ribasim model). These are influenced by infrastructure such as dams and weirs, which regulate flow and storage. All future scenarios project a decline in water availability in the Rhine basin. The average summer flow will decline due to changing climate by 6-11% ().

While intense rainfall events may still occur, overall summer water availability is expected to decrease, leading to more frequent and severe droughts. These developments will challenge the basin’s ability to maintain stable water levels, with implications for both ecosystems and human water use.

By 2050, the differences between the three scenarios remain relatively small (see). However, by 2100, the range of projected low flows widens considerably, introducing greater uncertainty (see Buitink et al., 2023). The Hd2050 scenario shows the lowest median flow, suggesting the greatest risk of low water availability. The Ld2050 and Md2050 scenarios show slightly higher flows, but still below the current reference levels. This figure highlights the increasing vulnerability of the Rhine’s summer discharge under climate change.

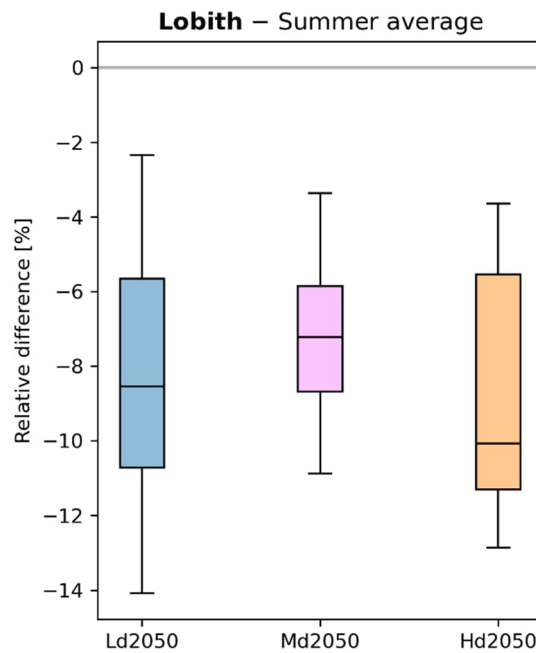


Figure 11: The three KNMI'23 scenarios Ld2050, Md2050 and Hd2050 for the Rhine basin show decreasing summer average flow at Lobith in comparison to the reference situation (Buitink et al, 2023)

How to read Figure 11?

The figure illustrates how summer average river flow at Lobith—a key downstream location in the Rhine basin—is expected to change under three climate scenarios for the year 2050: Ld2050, Md2050, and Hd2050.

What the figure shows:

- Each boxplot represents the distribution of summer average flow over a 90-year synthetic time series for one scenario.
- The box shows the interquartile range (IQR)—the middle 90% of values.
- The horizontal line inside the box marks the median flow.
- The whiskers extend to the minimum and maximum values

How to interpret:

- A lower median and compressed box indicate reduced and less variable summer flow.

6.2.2 Water availability in sub-basins

To better understand how these projected changes manifest across the basin, we now zoom in on the sub-basin level. Figure 12 depicts the distribution of discharges for the current situation and three future climate scenarios across eight sub-basins (excluding the Rhine Delta).

These results reflect natural discharges only, prior to the application of socio-economic scenarios or water demand time series. The boxplots represent cumulative discharges generated per basin, which—assuming no infrastructure or capacity constraints—can be considered the surface water available to meet demand within each sub-basin.

The results show a general decline in water availability as climate change becomes more extreme. Among the sub-basins, the Mosel/Saar and High Rhine exhibit the highest discharges.

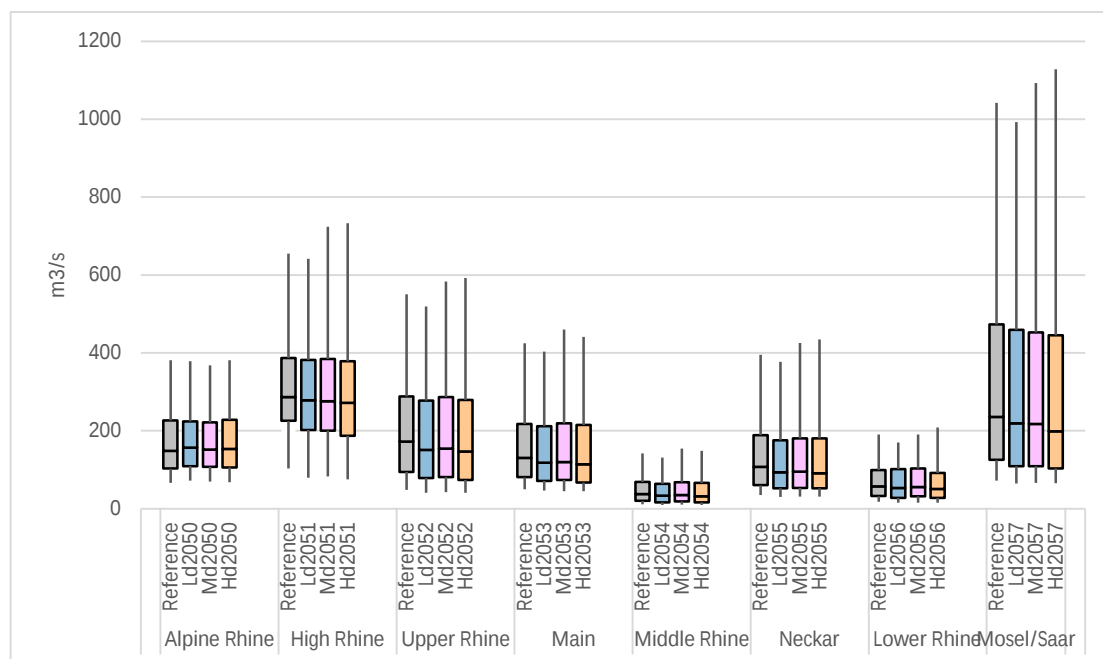


Figure 12: Water available per sub-basin to meet sectoral water demands per scenario (based on 90 -years hydrological timeseries)

6.2.3 Spatial distribution of low flow events

An extreme low-flow event at Lobith does not necessarily coincide with extreme low flows at other locations in the Rhine basin. To explore this, hydrological years were ranked based on the return period of the 7-day minimum flow at Lobith.

Return periods were calculated using frequency analysis, where each discharge value was ranked and its exceedance probability estimated. Specifically, the return period T for a given rank r in a dataset of size N was calculated using the formula:

$$T = N+1 / r$$

Table 11 presents the return periods of the 7-day minimum flow for each sub-basin across the 90-year synthetic time series. Each column represents a specific hydrological year, allowing for comparison of drought severity across locations.

The results show that while some sub-basins may experience droughts with high return periods (i.e., rare events), Lobith can simultaneously experience a low-flow event with a much lower return period. This suggests that droughts do not necessarily occur uniformly across the basin according to the KNMI'23 data.

Although this is a first indication based on modelled data, further research is needed to confirm these patterns. Recent drought events in Europe have shown that simultaneous droughts across regions are possible, and this phenomenon warrants closer investigation—such as in the ongoing CHR Rheinblick2027 study.

Table 11: Return period of 10-day minimum flow based on the 90-years of synthetic KNMI'23 data (current climate). Ranking of years with largest return period for Rhine discharge at location Lobith

	Rhine (Basel)	Neckar (Rocken- au)	Main (Raun- heim)	Nahe (Dieters- heim)	Moselle (Coche- m)	Lahn (Kalk- ofen)	Ruhr (Hat- tingen)	Lippe (Scher- beck)	Rhine (Lobith)
1	45.5	6.5	6.5	6.5	13	1.34	4.79	4.79	91
2	2.53	1.52	1.14	1.57	1.98	1.11	1.11	1.98	45.5
3	1.42	3.03	1.26	1.1	6.07	22.75	1.15	1.01	30.33
4	3.03	1.4	1.63	1.18	1.72	2.12	2.12	1.28	22.75
5	2.28	1.78	1.4	1.78	5.06	3.5	1.34	7.58	18.2
6	13	15.17	3.64	4.33	2.46	7	3.96	1.34	15.17
7	2.39	91	1.03	1.94	2.53	3.64	18.2	3.5	13
8	1.18	11.38	45.5	1.05	2.33	1.65	91	1.57	11.38
9	2.17	2.6	5.06	2.53	4.33	3.37	1.98	3.79	10.11

Having examined the spatial and temporal patterns of natural water availability, the next subchapter focuses on how water is used and demanded across sectors.

6.3 Water use and demand

The presented figures in this subchapter refer to water demand (total volume requested by each sector) and not the actual use. The actual use may be lower due to limited availability or infrastructure constraints. The analysis covers the Rhine basin upstream of Lobith (German–Dutch border) for the three sectors domestic, industrial and agricultural.

6.3.1 Temporal distribution of demand

Table 12 presents estimated total water demand (in m³/s) per sector in the current situation and across three climate change scenarios for the year 2050. Each scenario reflects a distinct narrative combining climate conditions and socioeconomic development.

Table 12: Sum of average annual total water demand (m³/s) modelled per scenario and sector

Sector	Current Situation (Reference)	Ld2050 + Sustainable Community	Md2050 + Middle of the Road	Hd2050 + Economic Growth
	(m ³ /s)	(m ³ /s)	(m ³ /s)	(m ³ /s)
Domestic	76.3	62.7	74.3	84.9
Industry	468.2	280.9	421.4	608.6
Agriculture	37.8	37.8	57.4	82.0

These values reflect how water demand shifts under different climate scenarios and socio-economic development:

- Domestic water use shows moderate variation, with lower demand in the sustainable narrative and higher demand in the economic growth narrative.
- Industrial demand is highly sensitive to socio-economic assumptions, ranging from a significant reduction under sustainability to a sharp increase under economic growth.
- Agricultural demand increases notably in narratives with higher development and climate pressure, reflecting intensified irrigation needs or expanded cultivation.

While Table 12 provides a useful overview of total annual water demand across sectors, it's equally important to understand how these demands fluctuate throughout the year.

Seasonal patterns—such as increased domestic use during summer months or agricultural irrigation during growing seasons—can significantly influence water stress and resource planning.

In the next section, we zoom into the assumptions for annual variation of each sector to better understand temporal dynamics and their implications for adaptive water management.

Domestic water demand is relatively small compared to other sectors —ranging from 75 to 95 m³/s—and shows minor seasonal fluctuations linked to temperature (Figure 13).

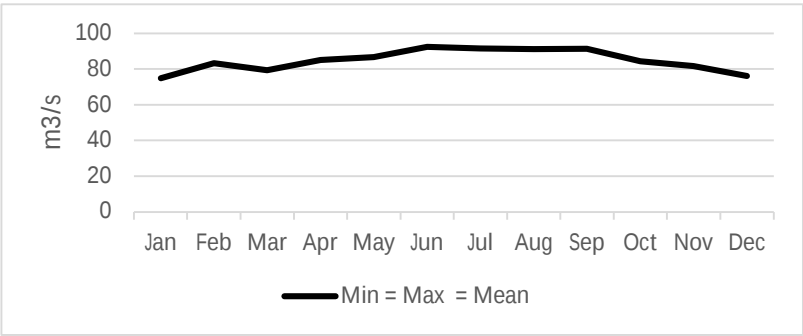


Figure 13: Projected domestic water demand in Rhine Economic Growth

Although industrial water demand—particularly for cooling water in power plants—is known to vary throughout the year, we have nevertheless assumed a uniform demand across all seasons for the purpose of this analysis. This simplification allows for a more straightforward comparison of water availability under different discharge scenarios. However, it is important to note that this assumption does not reflect real-world conditions. Cooling water needs are typically higher during warmer months due to increased ambient temperatures and elevated electricity demand. Additionally, operational schedules, maintenance periods, and environmental regulations can further influence industrial water use. As such, the uniform demand curve used here should be interpreted as a first-order approximation, with the understanding that actual demand may fluctuate significantly over time.

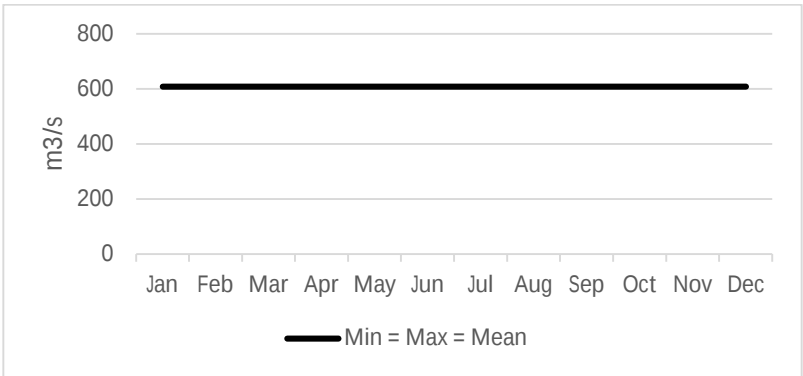


Figure 14: Projected industrial water demand in Rhine Economic Growth

Irrigation water demand peaks in June, July, and August, with significantly lower values during the rest of the year. This seasonal pattern reflects increased crop water needs during the summer. Projected irrigation demand ranges from 0 to 370 m³/s.

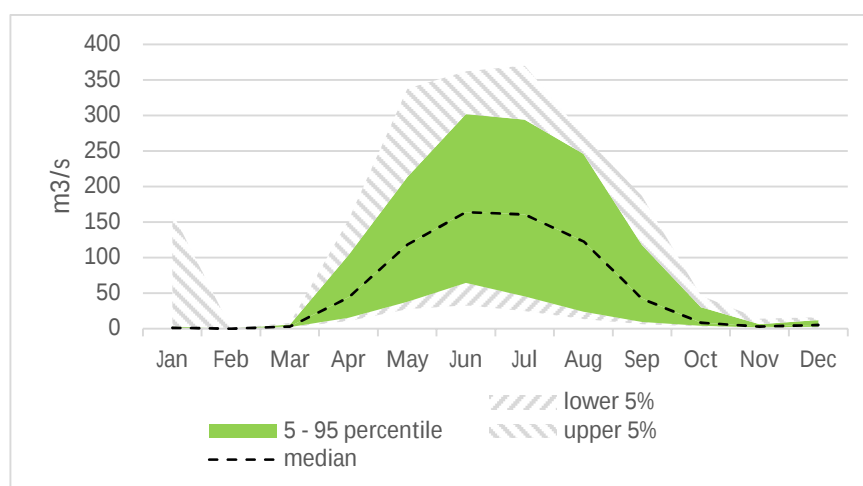


Figure 15: Irrigation water demand in Rhine Economic Growth - annual variation and differences between the modelled 90-years of the irrigation demand in the scenario

To explore high-demand conditions, one of these years (highlighted in green in Figure 15) was chosen for stress testing and used in subchapter 6.7 to assess water scarcity under peak demand conditions.

To assess how the Rhine basin might respond under peak stress conditions, we identified years with particularly high water demand. This helps simulate worst-case scenarios and supports the evaluation of potential shortages and trade-offs in water allocation.

To do this, we examined the annual averages across the full synthetic time series. Figure 16 shows the total average water demand (across all sectors) for each year in Rhine Economic Growth. Since the dataset is synthetic, the years do not correspond to actual historical years. Instead, each year represents a modelled hydrological year within the 90-year time series.

The selection of years was based on their annual average demand. The results show that years **#2001**, **#2007**, and **#2108** exhibit the highest total water demand.

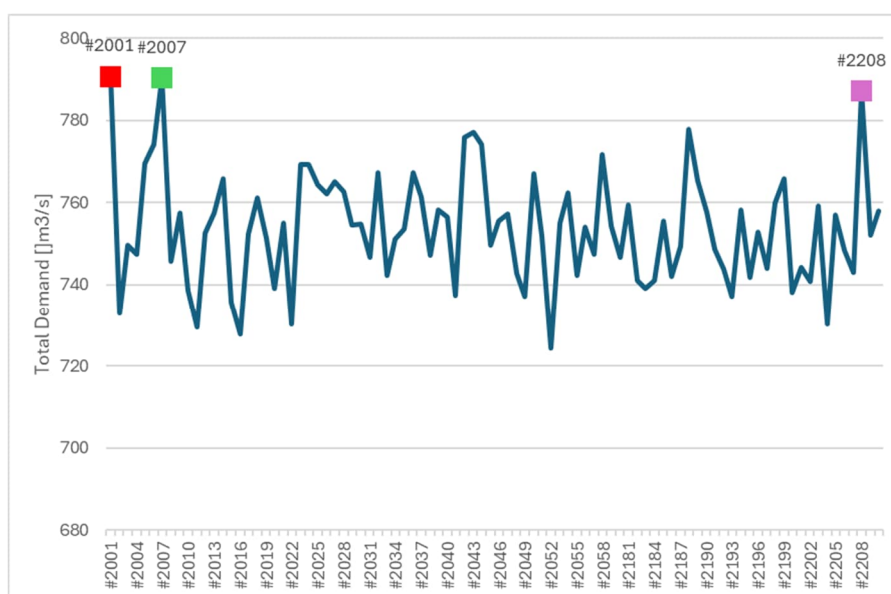


Figure 16: Average annual demand from all sectors in Rhine Economic Growth

Figure 17 illustrates the monthly variation in water demand for the three candidate years identified in the previous step. These years were selected based on their high annual average demand, but further screening was applied to ensure realistic seasonal patterns.

The blue shaded area represents the 5–95% percentile range of the dataset, indicating the typical monthly variation across the 90-year synthetic time series. The black lines show the full range of values—from minimum to maximum—including outliers.

Year #2001 was excluded due to an outlier in January that falls outside the 95% range, suggesting an unrealistic spike. Year #2108 was also excluded, as it showed two unusually extreme months—May and July—which, while possible, are considered unlikely.

Year #2007 was selected for further analysis because its monthly values mostly fall within the 5–95% percentile range, without major outliers. This makes it a suitable candidate for stress testing under high-demand conditions.

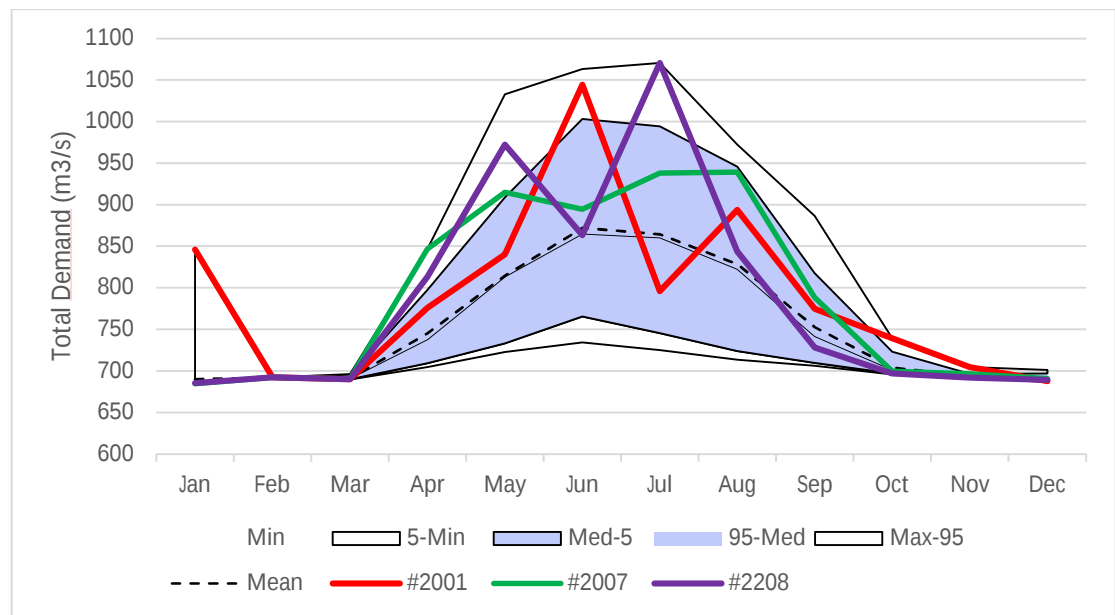


Figure 17: Three extreme high water demand years out of the 90 years timeseries are plotted in the bandwidth of the 90 years timeseries

How to read Figure 17:

The figure compares three synthetic years from the 90-year modelled time series to assess extreme water demand conditions in the Rhine basin. These years are labelled as #2001, #2007, and #2208—note that these are not actual calendar years, but reference numbers from the synthetic dataset used for scenario modelling.

What the figure shows:

Coloured lines represent monthly water demand for each selected year. The shaded area shows the 5–95% percentile range of monthly water demand across all 90 synthetic years—this gives a sense of typical variation. Black lines indicate the full range of values (minimum to maximum), including outliers.

How to interpret:

If a year's line stays within the shaded area, its monthly demand is considered typical. If it exceeds the shaded area, it may represent an outlier or unrealistic spike. Year #2007 was selected for further analysis because its monthly demand profile is consistently high but realistic, staying mostly within the expected range. Years #2001 and #2208 were excluded due to unusual peaks that fall outside the 95% range, suggesting they may not be representative of plausible stress conditions.

In summary, the selection of a representative high-demand year—based on both annual averages and realistic monthly variation—provides a robust basis for stress-testing the Rhine basin under peak water use conditions. Year #2007 was chosen for further analysis due to its consistent demand profile within the expected range, making it suitable for exploring potential shortages and allocation challenges.

Given that industrial demand is assumed to be constant and domestic demand is relatively small, the observed variation in total water demand is primarily driven by fluctuations in the agricultural sector. To better understand these dynamics, the next chapter focuses on the spatial distribution of water use per sector across the Rhine basin.

6.3.2 Spatial distribution of demand

Figure 18 presents a spatial comparison of water demand across the Rhine basin for three key sectors—domestic, industrial, and irrigation—under two different scenarios: the current reference situation and Rhine Economic Growth.

The figure is structured in two rows, with the top row showing the spatial distribution of sectoral water demand under current climate and socio-economic conditions, and the bottom row illustrating projected demand under the high-growth, high-emissions scenario. Each column corresponds to one sector, allowing for direct visual comparison.

The maps reveal that domestic water demand is relatively evenly distributed in both scenarios, with slight increases in urban areas under Rhine Economic Growth due to population growth.

Industrial demand, already high in the reference case, intensifies significantly in industrial hubs in the future scenario, reflecting economic expansion and increased cooling water needs.

Irrigation demand shows the most dramatic change, with minimal values in the reference case and sharp increases in Rhine Economic Growth, particularly in agriculturally intensive regions. This figure visually underscores the projected rise in water demand—especially for irrigation and industry—under a high-growth scenario, highlighting the spatial variability of future water stress across the basin.

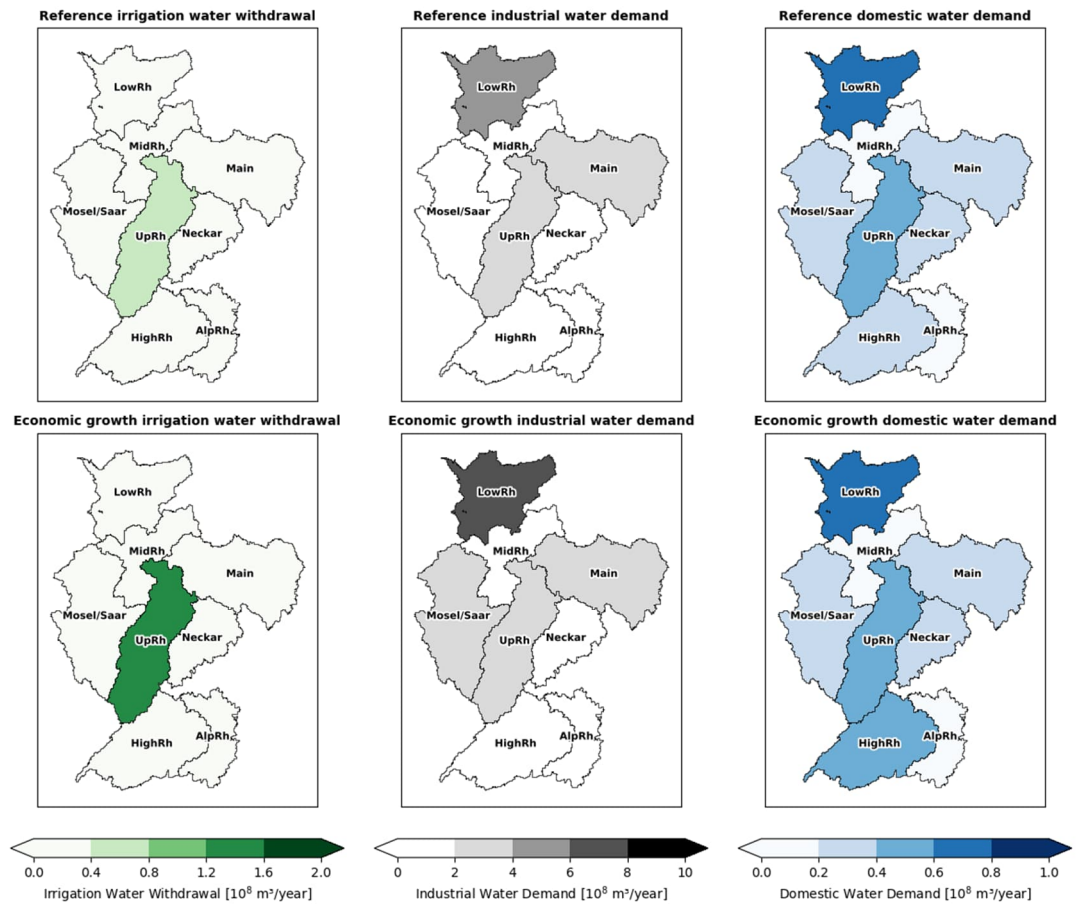


Figure 18: Spatial distribution of water demand estimates for domestic, industry and irrigation

6.4 Water scarcity

6.4.1 Water demand and shortage per sector and scenario

Building on the spatial analysis of sectoral water demand, this section explores how increased pressures on the system translate into actual constraints in meeting those demands. As demand intensifies—particularly under combined scenario Economic Growth and Hd2050 Climate Change—the balance between available surface water and sectoral needs becomes increasingly strained. This growing pressure manifests in the form of water shortages, which serve as a key indicator of water scarcity. Table 13 presents the demand and shortages per sector and scenario. The chapters thereafter focus on the presented shortages per sector and per scenario separately.

Table 13: Yearly averaged water demand and shortages per sector and scenario - based simulations with 90-years hydrological timeseries confronted with one year high water demand per scenario

Sector	Sub-basin	Current Situation (Reference)		Ld2050 + Sustainable Community		Md2050 + Middle of the Road		Hd2050 + Economic Growth	
		Demand (m3/s)	Shortage (m3/s)	Demand (m3/s)	Shortage (m3/s)	Demand (m3/s)	Shortage (m3/s)	Demand (m3/s)	Shortage (m3/s)
Domestic	Alpine Rhine	3.0	0.0	2.7	0.0	3.1	0.0	3.4	0.0
	High Rhine	11.1	0.0	10.0	0.0	11.6	0.0	12.7	0.0
	Main	10.0	0.0	8.0	0.0	9.5	0.0	11.0	0.0
	Middle Rhine	4.0	0.0	3.2	0.0	3.8	0.0	4.4	0.0
	Neckar	7.8	0.0	6.3	0.0	7.4	0.0	8.6	0.0
	Lower Rhine	19.8	0.0	15.8	0.0	18.8	0.0	21.7	0.0
	Upper Rhine	13.1	0.0	10.5	0.0	12.5	0.0	14.4	0.0
	Mosel/Saar	7.5	0.0	6.2	0.0	7.5	0.0	8.5	0.0
Industry	Alpine Rhine	9.0	0.0	5.4	0.0	8.1	0.0	11.7	0.0
	High Rhine	22.0	0.0	13.2	0.0	19.8	0.0	28.6	0.0
	Main	75.0	5.1	45.0	0.4	67.5	4.5	97.5	16.8
	Middle Rhine	30.9	3.1	18.6	0.6	27.8	2.7	40.2	8.2
	Neckar	44.2	1.9	26.5	0.1	39.8	1.8	57.5	6.8
	Lower Rhine	154.7	33.3	92.8	18.1	139.2	27.9	201.1	70.4
	Upper Rhine	77.7	5.4	46.6	1.3	69.9	5.3	101.0	17.0
	Mosel/Saar	54.7	0.1	32.8	0.0	49.2	0.0	71.1	1.6
Agriculture	Alpine Rhine	0.1	0.0	0.2	0.0	0.2	0.0	0.3	0.0
	High Rhine	0.4	0.0	0.5	0.0	0.8	0.0	1.1	0.0
	Main	0.6	0.0	0.8	0.0	1.2	0.0	1.7	0.0
	Middle Rhine	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Neckar	0.1	0.0	0.1	0.0	0.1	0.0	0.2	0.0
	Lower Rhine	0.1	0.0	1.3	0.0	1.9	0.0	2.8	0.0
	Upper Rhine	27.8	3.5	34.7	7.6	52.5	17.8	75.0	35.5
	Mosel/Saar	0.3	0.0	0.4	0.0	0.6	0.0	0.9	0.0
Totals	Domestic	76.3	0.0	62.7	0.0	74.3	0.0	84.9	0.0
	Industry	468.2	48.9	280.9	20.5	421.4	42.3	608.6	120.8
	Agriculture	29.4	3.5	37.8	7.6	57.4	17.8	82.0	35.5

6.4.2 Sector analyses

This section analyses water demand and associated shortages across three sectors—domestic, industry, and agriculture—under four combined scenarios: the current situation (Reference), Ld2050 + Sustainable Community, Md2050 + Middle of the Road, and Hd2050 + Economic Growth.

6.4.2.1 Domestic Sector

Domestic water demand remains relatively stable across all sub-basins and scenarios, ranging from 2 - 22 m³/s (see Figure 19). Importantly, no shortages are observed in any scenario for the domestic sector. This is due to the sectoral prioritization rules embedded in Ribasim Rhine Model, which allocate water first to domestic use, followed by industry and then agriculture. As a result, domestic needs are consistently met, even under increased demand and reduced water availability such as the Rhine Economic Growth Scenario.

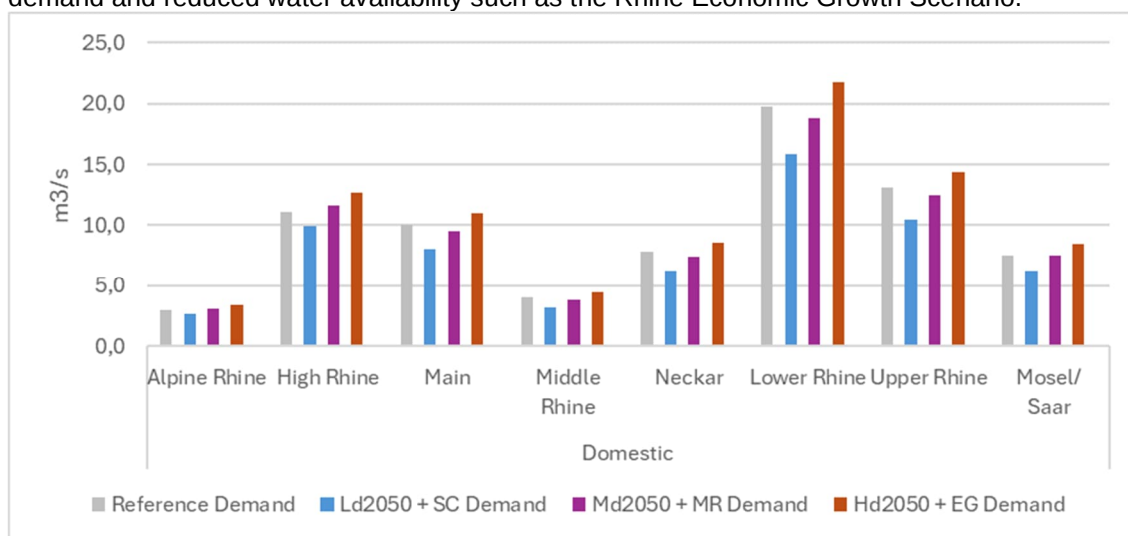


Figure 19: Domestic water demand and shortage (the model simulations indicated no shortages)

6.4.2.2 Industrial Sector

Industry shows the highest overall demand and the most significant shortages, especially under the Hd2050 + Economic Growth Scenario. Demand increases from 280.9 m³/s in the sustainable scenario to 608.6 m³/s in the economic growth scenario (see Table 13: Yearly averaged water demand and shortages per sector and scenario - based simulations with 90-years hydrological timeseries confronted with one year high water demand per scenario

). Corresponding shortages rise sharply from 20.5 m³/s to 120.8 m³/s, with the Lower Rhine, Main, and Upper Rhine sub-basins experiencing the largest deficits (see Figure 20). Despite its second-tier priority in allocation, industrial water use becomes increasingly constrained.

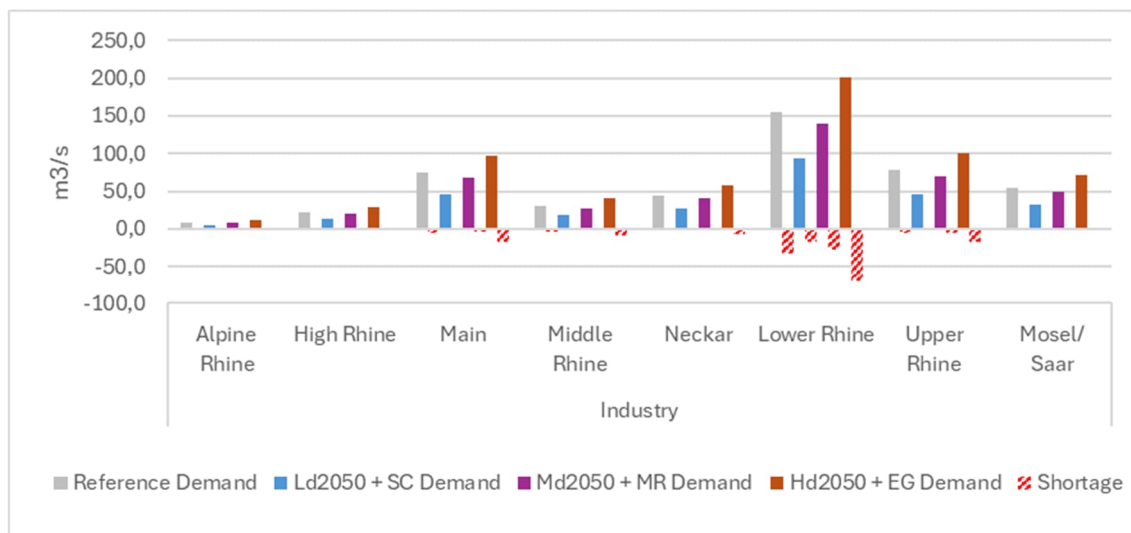


Figure 20: Industrial water demand and shortages per scenario

6.4.2.3 Agricultural Sector

Agricultural demand is the lowest in absolute terms but shows the highest relative uncertainty and variability, particularly in the Upper Rhine sub-basin. While total demand increases from 29,4 m³/s to 82.0 m³/s across scenarios, shortages also rise from 3.5 m³/s to 35.5 m³/s. As the lowest-priority sector in the Ribasim Rhine Model allocation hierarchy, agriculture is most vulnerable to supply constraints, especially under scenarios with increased competition and climate-sensitive demand.

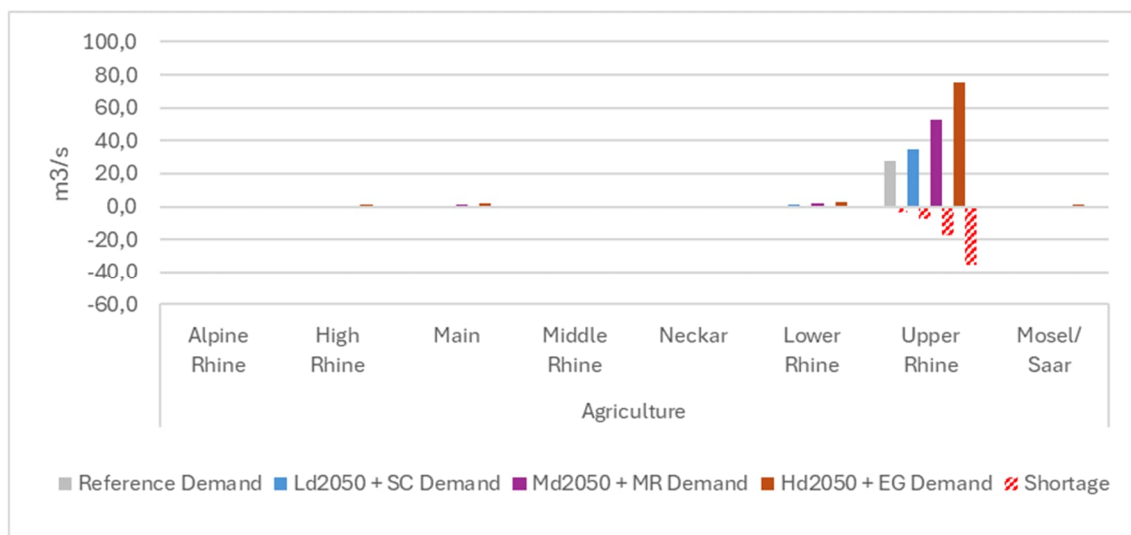


Figure 21: Agricultural water demand and shortages

The analysis of sectoral water demand and shortages across scenarios reveals distinct patterns. Industry emerges as the dominant water consumer, facing the greatest risk of shortages—particularly under the economic growth scenario—where demand peaks and deficits become substantial. In contrast, agriculture, while having the lowest absolute demand, has the highest relative uncertainty, driven by its sensitivity to climate variability. Meanwhile, domestic water use remains secure across all scenarios due to its highest prioritization in allocation. These findings highlight the need for scenario-based planning and sector-specific strategies to ensure resilient and equitable water distribution. Importantly, the observed shortages—especially in the industrial and agricultural sectors—may exacerbate low flow conditions in river systems, affecting ecological health and water availability downstream. These potential impacts will be explored in detail in the following chapter, which focuses on low flow dynamics under future scenarios.

6.5 Impact on low flow discharges

As water demand increases and shortages intensify across the Rhine basin, the consequences extend beyond local supply constraints and begin to affect the river system as a whole. Reduced availability of surface water—combined with higher abstraction rates—can lower discharges in the main river and its tributaries, pushing the system below critical thresholds. These low flow conditions have far-reaching implications: they jeopardize environmental flows needed to sustain aquatic ecosystems and water quality, and they compromise the reliability of inland navigation, particularly at key locations like Kaub and Lobith where minimum water depths are essential for shipping. As these pressures compound, maintaining a balance between human water use and the ecological and economic functions of the Rhine becomes increasingly challenging. This chapter explores how combined climate and socio-economic scenarios influence low flow discharges at strategic points along the Rhine, shedding light on the broader system-level impacts of growing water stress.

6.5.1 Low flow discharges at Basel, Kaub and Lobith

To describe the impacts of water shortages on overall discharges, three locations were selected across the Rhine basin. Location 1 is Basel, situated downstream of the Alpine Rhine, High Rhine (including Aare) tributaries. Location 2 is Kaub, located downstream of the Upper Rhine and the tributaries Neckar and Main. Location 3 is Lobith, situated at the delta apex on the border between Germany and the Netherlands. These locations were chosen to provide a comprehensive overview of how water supply and shortages affect discharges in different parts of the Rhine basin, highlighting variations and trends across these key areas.

To understand how low flow discharges respond to different climate and socio-economic futures, model simulations were conducted for each of the three selected locations. These simulations provide insights into how annual and seasonal discharge patterns are the current situation (Reference) and may evolve under Ld2050 + Sustainable Community, Md2050 + Middle of the Road, and Hd2050 + Economic Growth scenarios. The following sections present the results of these simulations, beginning with an analysis of annual average discharges and their seasonal variations.

6.5.2 Annual average discharges

Figure 22 compares low-flow conditions at Basel, Kaub, and Lobith for the current situation and three future scenarios, both excluding and including water demand. Generally, the annual average discharges declines at all locations in the reference and all future scenarios, reinforcing the overall trend toward reduced water availability under climate change and increasing demand. Several trends emerge. The relative difference from the reference scenario becomes increasingly pronounced from Ld2050 to Md2050 and then to Hd2050, indicating stronger impacts over these scenarios. Furthermore, by comparing the boxes for cases excluding and including water demand, we observe that the influence of water demand grows progressively across these scenarios.

How to read Figure 22, Figure 23, Figure 24, Figure 25?

What the figure shows:

The figures show the range of low-flow conditions at three key Rhine locations under present and future scenarios. Each box represents the distribution of low flows over the 90-year modelled period, expressed as a relative difference from the reference scenario (all values are below zero because every scenario reduces low flows).

Light colours indicate time series excluding water demand (climate impact only), while dark colours include water demand (climate + demand). The first grey box shows the difference between the reference scenario with and without water demand. The grey boxes following each scenario illustrate the additional effect of water demand on low flows.

How to interpret

- Compare light vs. dark boxes within each scenario to see how water demand amplifies reductions.
- Grey boxes help isolate the impact of demand alone.
- Moving from Ld2050 → Md2050 → Hd2050, reductions become more severe, especially when demand is included.

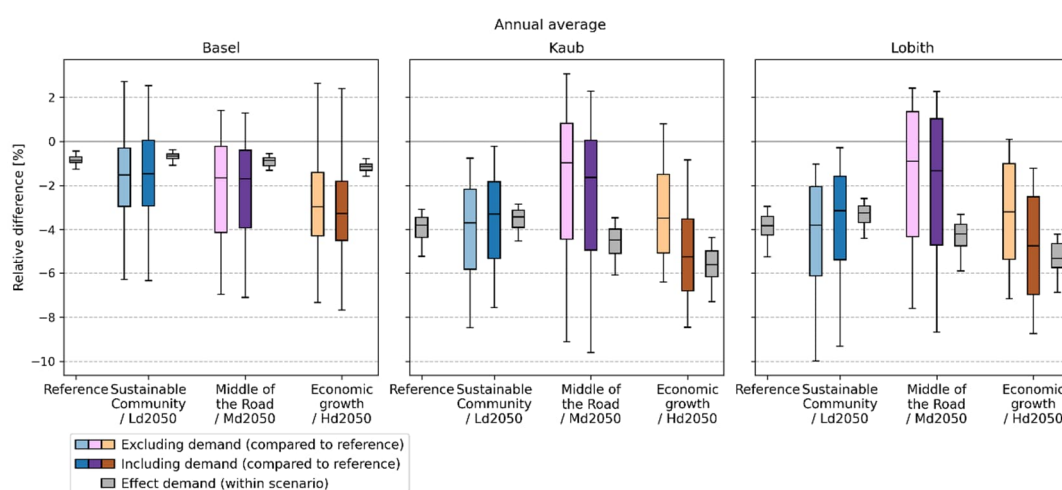


Figure 22: Annual average in Basel, Kaub and Lobith in all three scenarios

Figure 23 illustrates summer low-flow conditions at Basel, Kaub, and Lobith for the current situation and three future scenarios, both excluding and including water demand. Several patterns emerge. The relative difference compared to the reference scenario becomes increasingly pronounced from Ld2050 to Md2050 and then to Hd2050. Comparing the boxes for cases excluding and including water demand reveals that the influence of water demand grows progressively across these scenarios. Overall, the figure highlights that summer low flows decline at all locations in all future scenarios, underscoring the combined effect of climate change and rising water demand on seasonal water availability.

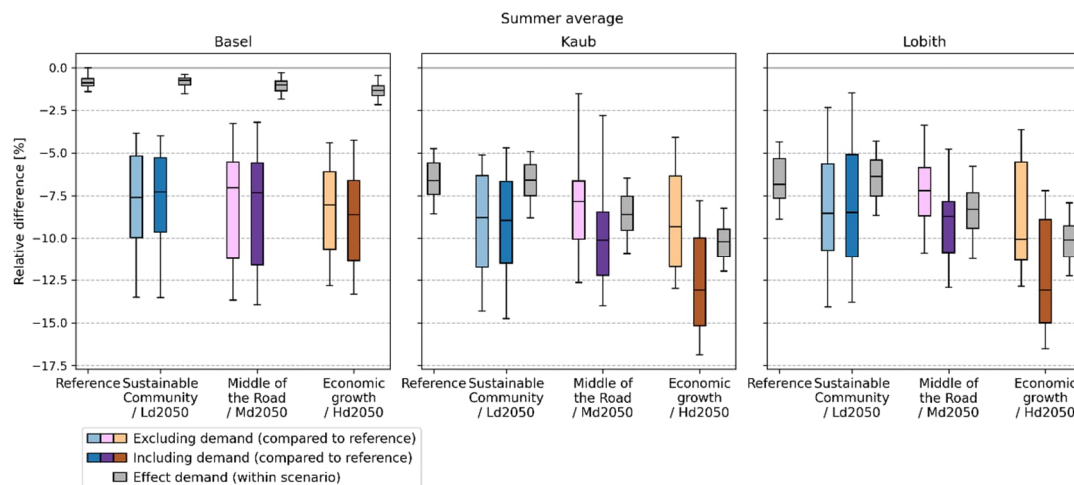


Figure 23: Summer average in Basel, Kaub and Lobith in all three scenarios

6.5.3 Minimum flow levels over 10 days

While annual and seasonal averages provide a broad understanding of how discharges may evolve under different scenarios, they do not fully capture the critical low-flow conditions that pose the greatest challenges for water management.

To better assess the severity and frequency of these events, this section focuses on the Normal Minimum Discharge over 10 days (NM10Q)—a key hydrological indicator representing the average of the lowest discharges recorded over a continuous 10-day period. NM10Q is particularly relevant during extended dry spells in summer, when both natural availability and competing demands are at their most extreme. It supports planning for ecological flow requirements, navigation, and other critical uses by identifying periods when discharges fall below operational thresholds.

This metric is especially useful for understanding how climate change and increased water abstraction interact to intensify low flow conditions. Reduced precipitation, higher evaporation rates, and growing water demand all contribute to lower NM10Q values, pushing the system closer to critical thresholds for environmental flows and navigability.

Figure 24 illustrates changes in summer low-flow conditions (NM10Q) at Basel, Kaub, and Lobith under different future scenarios excluding and including water demand. Several key observations emerge. First, all future scenarios show reductions compared to the reference, with the most pronounced declines occurring in Hd2050, reflecting the combined impact of climate change and economic growth. Second, the effect of water demand becomes increasingly significant, as shown by the difference between the blue and purple boxes; including demand amplifies reductions, particularly in Hd2050. Third, while Basel, Kaub, and Lobith follow similar trends, the magnitude of decline varies slightly across locations. Finally, the differences between the cases with and without water demand shows that the demand alone contributes substantially to the reduction, although climate remains the dominant driver.

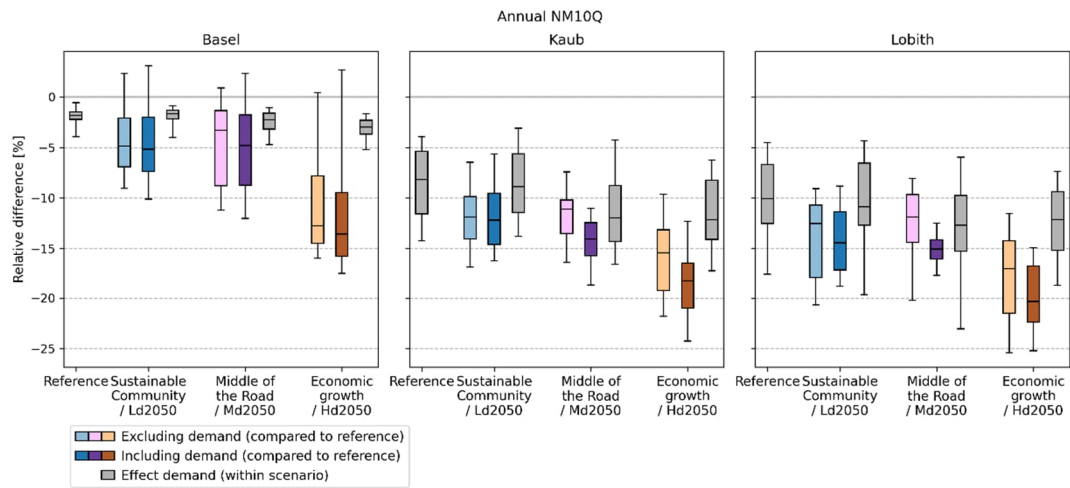


Figure 24: Annual NM10Q in Basel, Kaub and Lobith in all three scenarios

Figure 25 presents the relative change in summer low-flow conditions (NM10Q) at Basel, Kaub, and Lobith under different future scenarios. While overall patterns remain consistent, the reductions become more pronounced across scenarios: all future conditions show declines compared to the reference, with the most severe reductions occurring in Hd2050 (Economic Growth). The comparison between cases including and excluding water demand reveals a clear and growing difference, indicating that the impact of water demand intensifies progressively from Ld2050 to Md2050 to Hd2050.

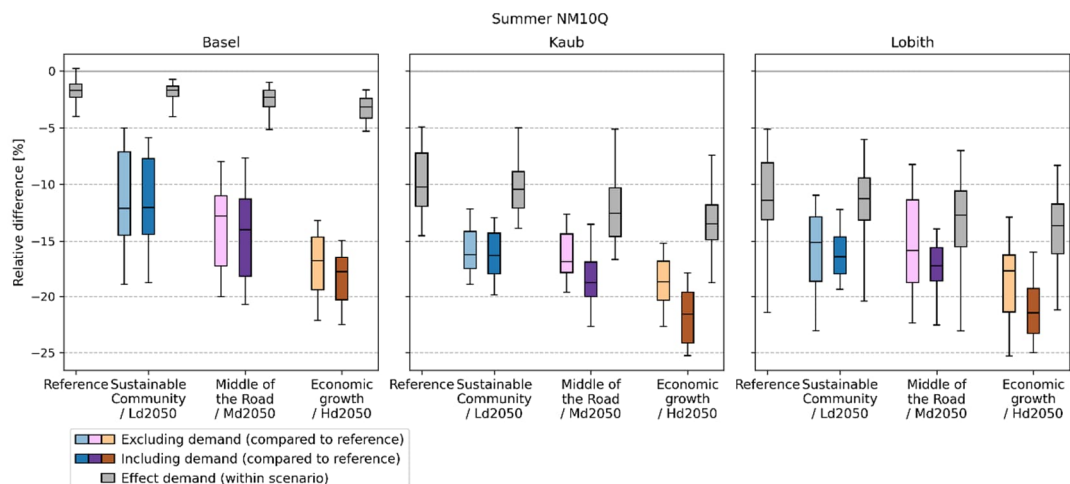


Figure 25: Summer NM10Q in Basel, Kaub and Lobith in all three scenarios

Future summers will see lower and more critical low-flow conditions, driven by both climate change and increasing water demand. Here is a summary of the outcomes on low-flows:

- Consistent decline in low flows: All scenarios show reductions in summer low-flow conditions (NM10Q) compared to the reference, indicating significant climate-driven impacts.
- Scenario severity matters: Reductions become progressively larger from Ld2050 Sustainable Community to Md2050 Middle of the Road, and are most severe in Hd2050 Economic Growth.
- Water demand amplifies impacts: Scenarios including demand result in greater reductions than scenarios excluding demand, especially in Hd2050 Economic Growth.

- Location differences exist: Basel, Kaub, and Lobith follow similar trends, but the magnitude of change varies slightly, with an increase in downstream direction

6.6 Water availability, demand and shortages for the Delta-Rhine subbasin

The previous sections focused on low flow discharges at key locations along the Rhine, highlighting how upstream water demand and climate change can reduce flows and increase stress on the river system. These impacts are particularly relevant for the downstream Delta-Rhine region, where freshwater availability is critical for multiple functions, including flushing to prevent saltwater intrusion and maintaining water levels for peatland preservation and dike safety, and mainly depend on the flow at location Lobith.

Mens et al. (2024) conducted a study on the freshwater balances of the Netherlands during drought conditions, analysing how these balances may shift under the combined influence of climate change, socio-economic developments, and sea level rise. Drawing on insights from the Dutch Delta Programme's "basic projections freshwater" and the Sea Level Rise Knowledge Programme, the study developed a simplified scenario assessment to estimate potential water shortages in the lower Rhine-Meuse delta. The components of the water balance are illustrated in Figure 26. Most freshwater enters the Netherlands via the Rhine and Meuse rivers, but during low water periods, the Rhine contributes significantly more than the Meuse (Buitink et al., 2023).

Downstream of Lobith (Rhine) and Monsin (Meuse), water is primarily used for flushing (to counteract saltwater intrusion from the sea) and for maintaining water levels in low-lying areas. In this analysis, it is assumed that domestic and industrial water supply can be met through the volumes allocated for flushing. The contribution of the Meuse is excluded, as historical data show that it provides little to no additional flow during low water events. Under the most severe scenario, the model projects that upstream water demand could reduce Rhine discharge in July (in a dry year with a 1-in-20 return period) by approximately 60 m³/s, resulting in an estimated water shortage of around 230 m³/s in the Delta region (see Table 14). In contrast, under average conditions, Rhine inflow remains sufficient to meet freshwater demands sustainably.

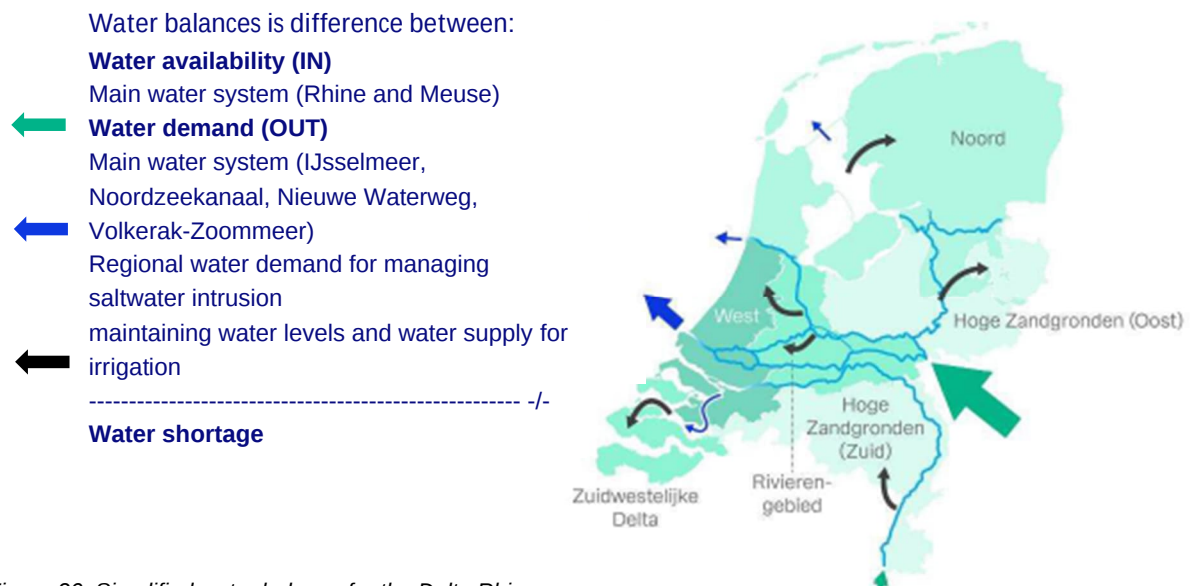


Figure 26: Simplified water balance for the Delta Rhine

Table 14: Water balances for the Delta-Rhine in the reference situation and under the Economic Growth/Hd 2050 scenario

Scenario	Reference	EG/Hd2050	Reference	EG/Hd2050	Reference	EG/Hd2050	Reference	EG/Hd2050
Situation	Yearly average		Summer average (April-Sept)		Average in July (dry month)		July in dry year (T= 20 yrs)	
Water demand (m3/s)								
Maintaining water levels in peat areas	0	0	19	24	25	33	68	95
Irrigated agriculture	0	0	5	12	11	27	19	38
Flushing polders and boezems	0	0	28	54	28	57	52	83
Flushing rivers and lakes (counteract salt water intrusion from the sea)	635	635	635	635	635	635	635	635
Water availability at Lobith available for water supply (m3/s)	2244	2140	1715	1492	1568	1339	850	620
Surplus (+) or Shortage (-) (m3/s)	1609	1505	1028	767	870	587	75	-231

7 Conclusions, reflections and recommendations

In the SES project (2023-2025) three scenarios were co-designed with stakeholders for the Rhine basin, each addressing a different plausible future. The focus is on balancing water availability, demand, and use in the (sub)basin(s) to assess their impact on the Rhine River discharge in 2050 and water allocation strategies, all in transboundary context:

1. *Sustainable Community*: By 2050, environmental protection is central. Rhine countries prioritise green energy and community-driven initiatives, with strong civil societies collaborating locally. The accompanying global climate scenario is low.
2. *Middle of the Road*: By 2050, moderate trends from 2020 have led to balanced economic and population growth. Rhine countries continue to rely on fossil fuels, with a gradual transition to renewable energy. The accompanying climate scenario is moderate.
3. *Economic Growth*: By 2050, Rhine countries focus on competitive markets, innovation, and private sector involvement. Intensive agriculture and industrial activities drive rapid technological progress. The accompanying climate scenario is high.

These scenarios were combined with regional climate change scenarios for 2050 created by KNMI for the Rhine River basin: Low, Medium and High scenario, each for the dry edition of the scenarios; so Ld2050, Md2050 and Hd2050 scenarios.

All narratives are described qualitatively and quantitatively and translated into model input. Model validation was conducted by comparison with other hydrological and water demand datasets and expert judgement. Model simulations assessed the impact of changing water demand under climate change on water balances and Rhine river discharges, in case water is allocated to water users by surface water in each subbasin (groundwater abstractions or water transfers from the main river are not taken into account).

7.1 Summary of key findings

Four key themes emerged from the results, each with implications for drought preparedness, water allocation, and long-term planning across the basin.

1. **Reduced water availability during summer months:**

The CHR ASGII and ICPR HCLIM based on IPCC AR4 and AR5 indicated that water availability during summer periods will decline and that we need to prepare for more frequent dry summers, which one currently still considers exceptional. This study reconfirms this. As a result, one may experience less **water availability** and water shortages more often towards the future. Whether drought also leads to water shortages depends partly on the availability of surface water from the rivers, lakes and reservoirs, i.e. on the coincidence of drought with low discharges and low storages. In this project we analysed the water availability according to the Ld2050, Md2050 and Hd2050 scenarios of KNMI'23 in more detail. The mutual difference between the three climate change scenarios in 2050 is still relatively small. The spatial distribution of drought events (coincidence) over the sub-basins is one of the themes that require more research (e.g. in CHR Rheinblick2027).

2. **Changing water demand and water use:**

Based on the new transboundary Rhine socio-economic scenarios **water demand and use** is expected to change, especially during summer and dry periods and in the Economic Growth scenario. Industrial water sector will stay the largest water user. Irrigated agriculture will see the most significant increase, though it remains a smaller user compared to industry and depending on the season of the year.

3. Shortages for different water sectors (domestic, industry and agriculture):

In the assessment - based on modelling combined KNMI'23 and Rhine socio-economic scenarios - one assumed that all water supply is provided by surface water and that domestic water supply has higher priority above industry water supply and industrial water supply is higher ranked than water supply for irrigated agriculture. Results of internal water balances per subbasin, indicate that domestic sector is not expected to face **water shortages**. However, industry will experience shortages in all scenarios due to high demand. Agriculture may face shortages under moderate climate scenarios or significant economic growth. Upper Rhine, Main, and Lower Rhine regions are expected to experience the most significant shortages. All is based on the under the assumption that domestic water is identified as the user with the highest priority in ranking for water allocation, then industry, before irrigated agriculture.

4. Rhine low flows will continue to decline:

Rhine river low flows are declining due to climate change. Growing water demand and use by households, industries, energy production and agriculture will worsen this and will increase **impacts**. Re-use of water or a high fraction of return flow from water users (e.g. through sewerage plants) will reduce the impacts partly. River flows are crucial for ecosystems, environmental health and good water quality. Lower discharges can disrupt navigation and have economic consequences basin wide. More low flows in combination with more salt water intrusion as a result of sea level rise under climate change, will put more stress on water management in the delta region of the Rhine water system. Effective, sustainable, and basin-wide low water management is essential.

7.2 Interpretation and Implications

The projected decline in summer water availability across all scenarios suggests that what is currently considered exceptional drought may become a regular occurrence by 2050. This shift has significant implications for water resource planning, requiring a transition from reactive to proactive drought management. The relatively small differences between the Ld2050, Md2050, and Hd2050 climate change scenarios highlight that even moderate climate change can lead to substantial impacts. Moreover, the spatial coincidence of drought events across sub-basins introduces complexity in regional water sharing and reservoir operations. These findings underscore the need for basin-wide coordination and further research into localized drought dynamics.

The socio-economic scenarios reveal that water demand will rise, particularly during dry periods and under the Economic Growth pathway. Industrial use remains dominant, but the sharp increase in irrigated agriculture—especially in summer—signals a growing competition for water resources. This trend implies that future water allocation strategies must account for seasonal and sectoral variability, and that agricultural planning should integrate climate-resilient practices. The findings also suggest that economic development without corresponding water efficiency or water re-use measures could exacerbate stress on already limited resources, reinforcing the importance of integrating socio-economic planning with hydrological modelling.

The prioritization of domestic water supply over industrial and agricultural use reflects current policy norms, but the modelling shows that even with this hierarchy, industry and agriculture are vulnerable to shortages in case they depend silo on surface water. Industrial sectors face consistent deficits across all scenarios due to high demand, while agriculture is particularly exposed under moderate climate change or strong economic growth. These results imply that surface water allocation policies may need to be revisited, especially in regions like the Upper Rhine, Main, and Lower Rhine, where shortages are most pronounced. In addition to reassessing sectoral priorities within countries, transboundary coordination could benefit from

a critical evaluation of **cross-border prioritization**—for example, whether upstream agricultural use should be limited to safeguard downstream domestic supply. Such discussions are essential for equitable and efficient water sharing in a changing climate. Strategic planning, including demand management and alternative water sources, including groundwater, will be key to mitigating sectoral impacts and maintaining economic and ecological stability.

The continued decline in Rhine low flows, compounded by rising water demand and climate-induced sea level rise, presents a serious challenge for basin-wide water management. Low flows affect not only ecological health and water quality but also nature, navigation and other economic activities. The increased risk of saltwater intrusion in the delta region and the necessary fresh water use to respond to this (flushing, maintaining water levels, etc.), further complicates freshwater availability and allocation. These findings highlight the urgency of developing sustainable, basin-wide low water management strategies that integrate flow regulation, ecological protection, and infrastructure adaptation. Long-term resilience will depend on coordinated action across sectors and borders, supported by robust monitoring and flexible policy frameworks.

7.3 Limitations

Some limitations of this study are:

1. Data gaps and harmonization

Despite extensive efforts to compile environmental, infrastructure, and socio-economic data from global to local sources, the study faced challenges related to data availability and consistency. Differences in definitions, spatial and temporal coverage across countries and sectors required harmonization and, in some cases, estimation. These adjustments may introduce uncertainties into the model inputs and outputs.

2. Scenario uncertainty

The study relies on plausible future scenarios—both socio-economic and climatic—to explore potential developments in the Rhine basin. While these scenarios are carefully constructed and grounded in expert input, they remain speculative by nature. Assumptions about economic growth, land use, technological development, and policy trajectories may not fully capture future realities, especially in light of unforeseen events or shifts. This inherent uncertainty means that the results should be interpreted as indicative rather than predictive, and used to support flexible, adaptive planning rather than fixed strategies.

3. Modelling assumptions

In the modelling exercises assumptions are made about water availability and use, water allocation priorities, infrastructure operation, and sectoral behaviour under stress. All assumptions were made aiming at studying impacts of droughts and low flows. For example, modelling surface water as a silo source (no groundwater abstractions) for water supply is a stress test of the water resources system. Combined with a the target level for supply that represents the water demand under extreme dry conditions (water demand peaks) creates a further stress for the Rhine water resources system. The implemented prioritization of domestic water supply over industrial and agricultural use reflects a normative hierarchy that may vary in practice, especially during water crisis situations. Similarly, assumptions about reservoir operations, abstraction (no-)limits and fractions of return flow may not fully reflect real-world flexibility or dynamics, and might be updated in future studies.

4. Assessment of adaptive measures

The primary focus of this project was to assess future water stress under different scenarios, rather than to evaluate specific adaptation strategies. As a result, the modelling does not account for potential mitigation measures such as improved irrigation efficiency, demand management policies or groundwater as a conjunctive water resource. Including such measures in future modelling efforts would allow for better understanding of resilience pathways and help identify effective interventions under different future conditions.

7.4 Recommendations

The first interpretation of the KNMI'23 climate scenarios in combination with the novel co-designed socio-economic scenarios in the transboundary Rhine basin highlights a pressing need for enhanced preparedness for droughts and freshwater availability—not only nationally but also across borders. The climate change scenarios already indicated that dry summers, currently considered exceptional, are likely to become more frequent. When water demand and use are explicitly taken into account this shift increases the risk of water shortages beyond what was previously projected.

In a transboundary context, the occurrence of drought- and water use-related low water levels is closely tied to the availability of river discharges from cross-boundary tributaries to the main Rhine trajectory. Specifically, coincidence of regional droughts with low river discharges can significantly impact upstream, midstream and downstream water security further and requires further research. To be able to develop international water allocation strategies, navigation and e-flows or reduced river discharge below operational thresholds must be considered in a follow-up study, in addition to water consumer categories (domestic, industry and irrigation).

Two key priorities emerge for strengthening the transboundary knowledge base in support of informed planning and decision making:

- Incorporating socio-economic insights, integrated with climate change insights, into cross-border water management and policy frameworks, ensuring that integrated river basin planning reflects shared vulnerabilities and coordinated responses.
- Expanding comprehensive system knowledge from the perspective of the entire international river basin, recognizing that water use and hydrological impacts and adaptation strategies must be jointly assessed and implemented.

Finally, active cooperation with the Rhine Commissions, European, national and regional authorities, and (inter)national knowledge institutes is essential to broaden and harmonize the understanding of water use impacts under climate change across the basin. This joint effort will support more resilient and equitable water governance in the face of increasing climate variability.

7.5 Future research

During the SES project (2023-2025), a range of ideas for future research and development emerged—some as part of ongoing or planned activities within the STARS4Water project, and others as exploratory suggestions or wishes voiced by stakeholders. These are not formal recommendations or commitments, but rather reflections and brainstorming that may inspire future work.

For example, the concept of defining a “safe operating space” for water resources management is already under development within STARS4Water, alongside tools for environmental flow (e-flow) assessment and agricultural water demand modelling using satellite data.

Other ideas, such as integrating groundwater dynamics into the modelling framework—through coupling with Modflow or incorporating insights from projects like WadKlim—were raised by stakeholders as desirable next steps.

Suggestions also included refining indicators for transboundary water resilience, expanding scenario design in collaboration with Rhine commissions, and exploring land use modelling to assess socio-economic impacts.

Technical improvements to the IWRM Rhine Modelling Framework, such as linking with sectoral tools for navigation and ecology or enhancing reservoir operation modelling, were also discussed.

These reflections highlight the creative momentum generated during the project and point to promising directions for future collaboration, innovation, and knowledge exchange.

7.5.1 To further improve the scenarios and model study

To further improve the scenarios and model study the project team together with stakeholders suggest:

- Continue the discussion on collaborative scenario design with representatives of institutions in different Rhine countries, ICPR, CCNR and compare results to other scenario studies. E.g. in the frame of its Rhine 2040 programme and further investigations on water availability, demand, and use, the ICPR expressed-wishes to contribute to and benefit from future CHR modelling activities (e.g. via Ribasim and the integration of updated data).
- Evaluate the indicators that are studied and discuss them with representatives of the Rhine commissions to arrive at an indicator and evaluation framework for transboundary water resilience and security and/or “safe operating space” for water resources management.
- Further examination of water demand and use data based on more in-depth analyses and literature and further interviews and research. Collect additional information and data related to water infrastructure and supply system: location of main water abstractions, incl. sources of abstraction, main infrastructure for water supply, etc.
- Extend the water demand and use analyses with aspect of water availability and needs for the ecosystem but also consequences of water shortages for nature. This could be handled for example through the use of e-flows (see ongoing research below) and definition of thresholds for the environment. This could be done in cooperation with among others the Working Group “Ecology” of the ICPR.
- Extend the river flow and use analyses for inland navigation, studying minimum thresholds for low flows (for example GIW and GIQ indicators), in cooperation with among others the CCNR.
- Perform a sensitivity analysis on water allocation assumptions and priorities among water users as well as fraction of return flows. E.g. change the initial assumptions and priorities of use: for instance, the assumption that agriculture is more important than industry. Include aspects of navigation and nature as well.
- Collaborate with reservoir operators to include local operational rules and area-volume-level relations in the model and/or start experimenting with data science technologies for estimations based on satellite data and monitoring on the ground.

- Develop a storyline for SSP3/RCP6 to have the cornerstone of the full range of IPCC scenarios.
- Explore measures and strategies to reduce the impacts projected by the narratives and modelling results and discuss how they should be simulated in the IWRM Rhine Modelling Framework.

7.5.2 To further improve the modelling framework

To further improve the modelling framework the project team together with stakeholders suggest:

- Discuss how to incorporate groundwater levels and flows, e.g. by coupling with a Modflow model for the Rhine basin.
- Consider making the connection with the available state-of-the-art Ribasim model in the Netherlands and also shift for the Rhine model to this next generation Ribasim software version to enable seamless, online timestep integration with groundwater, hydrological, reservoir management and water allocation modelling towards comprehensive description of the water system.
- Explore the development of a simple land use and land cover model for the Rhine basin to scan and model the land use changes based on socio-economic scenarios (The Netherlands has such a “ruimtescanner” (“spatial scanner” in English).
- The IWRM Rhine Modelling Framework can be extended by linking with other sectoral tools, such as those for inland shipping impact assessment, e-flow assessments or optimising reservoir management.
- One update is already underway, including a novel agricultural water demand and irrigation water use model based on satellite data and land surface temperature, developed in the STARS4Water project. An e-flow assessment tool is also in development. These models could be integrated into the framework in collaboration with STARS4Water. Test model runs will take place in the upcoming months.

7.5.3 Potential future steps

As potential future steps the project team and/or engaged stakeholders, especially the ICPR, suggest:

- Enable access for the ICPR and other stakeholders (upon request) to all data and information used in and for the CHR SES report and calculations (request by ICPR)
- Establish a reliable mechanism between the ICPR, CHR, and other stakeholders to ensure continuity and enable the joint further development of the modelling tools, as well as new or more detailed calculations (e.g. in connection with Rheinblick2027 or a follow-up programme after 2027) (required by ICPR).
- Develop a joint recommendation from the three Rhine commissions to the states in the Rhine basin and the EU to address gaps in the currently available water use/demand data and to initiate improved data collection practices for the future.
- Make a further, more detailed comparison with the discharge scenarios that were collected by the ICPR (Report 297, EG HCLIM) as part of and/or in cooperation with the CHR Rheinblick2027 study.
- Develop a vision and strategy for further improve the model framework and transfer to a seamless IWRM model framework. A major update of the Ribasim modelling software (water allocation) is underway, with seamless coupling with Wflow (hydrology and water demand), Modflow (groundwater), RTC tools (reservoir operation modelling) and various demand tools (drinking water, industrial water, agricultural water) and the react tool for e-flow assessment)

- Future scenarios, projections, and related calculations should consider groundwater aspects, including interactions between phreatic aquifers, bank filtrates, and overall water availability, scarcity, and use. This should include insights from ongoing research (e.g. the German project *WadKlim*) and enhance the assessment of the positive impacts of organic farming and sustainable forestry, particularly in terms of water retention and groundwater recharge. (request by ICPR)

7.6 Final reflection

The SES project has laid a strong foundation for transboundary water cooperation in the Rhine basin by integrating climate and socio-economic scenario analysis with stakeholder-driven modelling.

Through collaborative efforts with CHR, ICPR, CCNR, and the EU STARS4Water project, the study addressed key questions on scenario availability, data infrastructure, and water allocation under future stress conditions. The co-designed narratives and the application of the IWRM Rhine Modelling Framework enabled a shared understanding of emerging risks and trade-offs, while also fostering dialogue across sectors and borders. As climate change and socio-economic pressures intensify, the project highlights the importance of adaptive, inclusive, and forward-looking water governance. Continued investment in data harmonization, stakeholder engagement, and scenario-based planning will be essential to build resilience and ensure equitable water management in the decades ahead.

Finally, reflecting on the progress made, we address the original questions formulated by the CHR:

1. **Available Socio-Economic Scenarios** in Rhine basin countries: An initial inventory of Socio-Economic Scenarios in countries was made in 2022, followed by further support in 2024. Information is stored in a digital archive.
2. **Scenarios developed by IPCC and EU commission:** We used the latest IPCC scenarios for inspiration, working with SSP1, SSP2, and SSP5 scenarios. The EU STARS4Water project supported the co-design approach for scenario development on the river basin scale.
3. **Defining, preparing, and assessing scenarios:** We co-designed three scenarios with stakeholders in the Rhine basin, incorporating their feedback. The scenarios are described in aspects of the biophysical environment, socio-economic developments, and expected impacts on water use.
4. **Improving data/set-up data repository and literature archive:** We started with the database of the Ribasim Rhine model (an integrated river basin management and water allocation model) developed in 2021 and collected further data. Follow-up meetings were scheduled to discuss data requests per country or region. Data and literature received are stored in a data and literature archive and where applicable, data was transferred to the Ribasim model, that has been updated. We connected the Ribasim Rhine model with the Wflow Rhine model (a hydrological model), being the core of the IWRM Rhine Modelling Framework.
5. **Taking joint and informed action:** The new transboundary socio-economic scenarios under climate change are co-designed with stakeholders. The scenarios come with a IWRM Rhine Modelling Framework enabling scenario analyses in water resources allocation and low flow conditions. First modelling runs and scenario assessments supported discussions on balancing water demand and availability, potential water shortages, and priorities in water allocation.

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A Annex – Detailed description of three scenario narratives for socio-economic developments for the Rhine basin

A.1 From SSPs to three narratives – key figures

To develop the socio-economic scenario narratives for the SES project (2023–2025), we used the global Shared Socioeconomic Pathways (SSPs) as a starting point for quantification (Table 15). Specifically, we aligned our three SES narratives with SSP1, SSP2, and SSP5 to reflect a range of plausible futures for the Rhine River basin:

- Rhine Sustainable Community corresponds to SSP1, emphasizing sustainability, environmental awareness, and cooperative governance.
- Rhine Middle of the Road aligns with SSP2, representing moderate socio-economic development and policy continuity.
- Rhine Economic Growth draws from SSP5, characterized by rapid economic expansion and high resource consumption.

The SSPs provided standardized global trajectories for key socio-economic indicators such as population growth, urbanization, and GDP development. To tailor these to the Rhine basin context, we extracted national-level data from SSP between 2020 and 2050 databases for the six Rhine countries — Austria, France, Germany, Luxembourg, the Netherlands, and Switzerland — and calculated average values across these countries. This approach allowed us to generate general regional estimates that informed the quantification of our SES narratives.

Table 15: Overview of some socio-economic key numbers for each of the Rhine countries, forming the foundation for the Rhine SES development (in black text: negative change in percentage, in green text: positive change in percentage)

	SSP 1	SSP2	SSP3	SSP 4	SSP5
	Sustainability	Middle of the Road	Regional Rivalry	Inequality	Fossil-fuelled development
1 Population Growth between 2020 and 2050 (IIASA-WiC POP, 2023)					
Austria	5%	4%	0%	0%	14%
France	6%	6%	7%	2%	10%
Germany	-2%	-3%	-5%	-6%	5%
Luxembourg	22%	21%	14%	16%	38%
Netherlands	3%	3%	2%	-2%	7%
Switzerland	13%	12%	8%	8%	25%
Average	8%	7%	4%	3%	17%
2 Urbanization between 2020 and 2050 (NCAR, 2013)					
Austria	16%	12%	2%	12%	16%
France	5%	5%	5%	5%	5%
Germany	11%	11%	4%	11%	11%
Luxembourg	7%	7%	7%	7%	7%
Netherlands	7%	7%	7%	7%	7%
Switzerland	11%	11%	4%	11%	11%
Average	10%	9%	5%	9%	10%
3 GDP PPP Average per year between 2020 and 2050 (OECD ENV-Growth, 2023)					
Austria	2,1%	1,8%	1,2%	1,9%	3,0%
France	2,2%	1,8%	1,3%	1,9%	2,9%
Germany	1,7%	1,3%	0,7%	1,5%	2,5%
Luxembourg	1,9%	1,8%	1,1%	1,6%	2,8%
Netherlands	2,1%	1,9%	1,2%	1,8%	3,0%
Switzerland	1,6%	1,4%	0,8%	1,3%	2,5%
Average	1,93%	1,67%	1,05%	1,67%	2,78%

Input for



SES narrative
1:
Rhine
Sustainable
Community

Input for



SES narrative
2:
Rhine Middle of
the Road

Input for

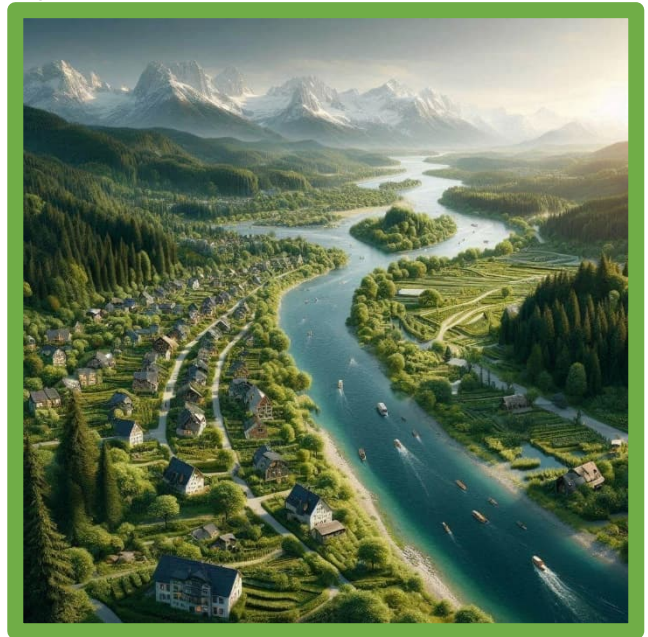


SES narrative
3:
Rhine
Economic
Growth

A.2 Description of the three narratives

A.2.1 Narrative 1: Rhine Sustainable Community

In the “Rhine Sustainable Community” scenario, environmental protection has become a central focus by 2050. All Rhine countries put significant effort towards a sustainable development and prioritizes green energy and community driven way of working. The Rhine countries have strong civil societies and collaborate very well on an local level with an eye on community resilience in the river basin. Environmental sustainability is now at the heart of the decision-making processes in the EU. Central aspects have become are human well-being and the acceptance of environmental boundaries. The accompanying global climate scenario is low.



A.2.1.1. Biophysical Environment

The natural environment in the Rhine catchment has experienced relatively moderate changes. Efforts to limit global warming to below 2°C have led to less severe impacts on ecosystems (RCP 2.6) and additional flushing and efforts to maintain water levels in peatland areas prevent from increased CO₂ emissions. The region has seen a slight increase in average temperatures and changes in precipitation patterns, but these changes are less extreme compared to higher emission scenarios. Biodiversity in the Rhine catchment has benefited from these mitigated climate impacts, with less stress on aquatic and terrestrial habitats. Additionally, there has been a declining influx of micropollutants and a reduction in fish migration obstacles, ensuring better habitat connectivity. Groundwater resources are being recharged and are not overexploited, contributing to improved water quality throughout the region.

Figure 27: Rhine Sustainable Community – Picture generated with Copilot (16.09.2024)

A.2.1.2. Socio-economic developments

Population growth

The primary factors influencing socio-economic conditions are the expansion of the population and the development of urban areas. The population has grown by 8% (IIASA, 2023 - SSP 1) from 2020 to 2050 and the Rhine basin is home to 61 million people, with a significant number residing in large cities along the river. While population trends differ among the countries in the Rhine region, they are generally on the rise, with Germany being the exception. The population in the Rhine catchment grew in most countries, with Austria experienced a moderate growth of 5%, France 6%, Luxembourg 21%, the Netherlands 3%, and Switzerland 13%. Despite having the largest population in the Rhine catchment, Germany experienced a decline of 2%.

Urbanization

Even with a modest increase in population, the growth is having been primarily focused in urban areas, contributing to ongoing urbanization. The process of urbanization persists, and existing large cities continue to expand.

The economies of the Rhine states remain politically stable, operating with efficient markets focusing on local economy and community collaboration. The urbanization rate has been 10% across the Rhine countries. The largest cities in the Rhine catchment such as Cologne, Frankfurt, Rotterdam, Stuttgart, Dusseldorf, Dortmund, Essen, Nuremberg, Duisburg, Strasbourg, Zurich, Utrecht, Bochum, Wuppertal, Bonn, Basel, Arnhem continue to grow. In Austria, urbanization is expected to increase by 16%. France sees a more modest increase of 5%. Germany and Switzerland both anticipate an 11% rise in urbanization. Luxembourg and the Netherlands are both projected to have a 7% increase (IIASA, 2023 - SSP 1).

Economic growth

Economic growth in the Rhine countries is showing positive trends, with a clear priority being placed on environmental protection and sustainable choices. Austria is experiencing an annual average growth rate of 2.1%, while France is slightly ahead with a rate of 2.2%. Germany is seeing a growth rate of 1.7%, and Luxembourg is close behind with 1.9%. The Netherlands matches Austria's growth at 2.1%, and Switzerland is experiencing a growth rate of 1.6% (IIASA, 2023 - SSP 1). On average, these countries are seeing an economic growth rate of 1.9%, indicating a growing economy in the Rhine region. This growth is not just about increasing wealth, but also about making responsible and sustainable choices. There is sufficient money available to adapt to climate change, and to invest in more sustainable technologies. These investments are seen as crucial for the long-term health and prosperity of the region. By prioritizing environmental protection, these countries are ensuring a sustainable future for their citizens and setting a positive example for the rest of the world. There is an additional focus on domestic interests and national security, which is also reflected in their economic choices.

Economic sectors

In the Rhine catchment area, free trade is flourishing within and between regions in the Rhine catchment, bolstered by stable and collaborative trade relationships between the European Union and Switzerland. Major economic sectors such as manufacturing, agriculture, trade and logistics, tourism, energy, and services have adjusted to new green policies, reflecting a shift towards sustainability. The agriculture and tourism sectors are transitioning towards more sustainable practices, enhancing recreational opportunities. Industrial sectors, while not significantly growing, are leveraging improved technology to conserve and protect the water resources of the Rhine catchment. Stricter environmental regulations are driving green innovation in the industry, leading to more efficient water and energy use. Simultaneously, the population's footprint is decreasing, resulting in lower energy and water use. This reduction is primarily due to technological improvements and a growing environmental awareness among the populace. Dietary patterns are shifting towards a planetary health diet, as recommended by the EAT Lancet commission, which includes less intake of dairy foods and meat. The agricultural sector is adapting to this change in demand and is transitioning towards a less intensive system that includes more arable farming and less livestock farming. This shift is also driven by stricter European environmental regulations, circular economy and rapid advancements in technology, which enable the maintenance of production efficiency with less input of resources.

Technology and innovation

Technological advancements in this scenario have been guided by a strong environmental agenda, with a particular focus on reducing pollution. These advancements have not only improved the efficiency and sustainability of transport along the Rhine River but have also helped to protect and preserve its ecological health.

Resource and Energy

The Rhine countries have prioritized renewable energy, resulting in significant increases in its share up to 2050.

The share of renewable energy in each Rhine country is as follows: France has reached 63%, Germany is at 74%, Luxembourg is at 46%, the Netherlands is at 53%, and Switzerland has achieved an 100% renewable energy (Estimation 1.1). These figures represent the absolute share of renewable energy in each country's energy mix. Looking ahead, targets will be set to phase out certain types of energy after 2050. Except France, this country will not phase out nuclear energy, recognizing its role in their energy strategy. Similarly, Switzerland will continue to rely on hydropower, given its significant contribution to the country's renewable energy portfolio. These decisions underscore each country's unique approach to balancing sustainability goals with their specific energy needs and resources. This commitment to a diverse and sustainable energy mix is a key aspect of the Rhine region's future. The target to increase to at least 40% renewable energy sources in the EU's overall energy mix in 2030 is reached and these trends has continued up to 2050.

SDG's and EU Green Deal

Major efforts are successful to integrate green aspects into Rhine catchment policies. The initiatives like the SDGs, EU Green Deal, and Water Framework Directive are fully embraced. The environment is given the utmost priority, nature and biodiversity are at the forefront of all considerations. This results in robust protection for all natural areas, including those outside the Natura2000 network. The growing population and housing demand are addressed with sustainable solutions that minimize encroachment on natural areas. Industry and agriculture are also carefully regulated to prevent expansion into these areas. This approach ensures the preservation of the natural area in the Rhine basin, which is safeguarded from pollution and water extraction. Despite the challenges, the focus remains steadfast on environmental conservation, demonstrating a strong commitment to ecological resilience and sustainability. Nature and biodiversity are protected and valued by the population for multiple ecosystem services and for support to reach climate mitigation and adaptation goals. There is an active afforestation plan, which led to an increase in forest areas. Peat and wetlands are well-maintained to limit emissions and increase carbon sequestration. As such, data is shared openly, and the system is managed and operated together with the countries of the Rhine basin. This means that major Rhine treaties is maintained.

Cooperation and decision making

Cooperation by the Rhine commissions will evolve significantly, focusing on harmonizing interests and addressing challenges, not only for the Rhine river but also on subbasins and communities driven. Flood risk management and water quality management will remain a priority, with ongoing efforts to reduce risks and strengthen awareness. Finding solutions in water allocation and prioritization, among different water users and between countries has gained priority. Decisions are oriented on local needs and tailored needs of sub-basins and communities. The approach includes holistic perspectives where environmental needs are prioritized.

A.2.1.3. Impacted water related sectors

The natural environment is expected to experience less severe impacts due to the implementation of major mitigation strategies. These strategies are aimed at addressing the challenges faced by biodiversity and forests. The goals of the EU birds and habitats directives, and Water Framework Directives have been met, leading to an increase in the quality of nature. In addition to quality, the quantity of nature also expands due to a growing demand for nature and the ecosystem services it provides. This results in an increase in the forest area in the Rhine basin. However, changes in hydrological patterns pose a threat to water quality during low-flow events, necessitating the implementation of adaptation strategies and minimum flow requirements. The conservation of rivers, peat, and wetland

areas gains importance not only for biodiversity conservation but also for climate mitigation. This emphasis on conservation leads to an increase in water demand for nature. The scenario also envisages the installation of fish traps at all sluices and locks in the river, further demonstrating a commitment to preserving the natural environment. Environmental recreation and green tourism will become an important economic sector in Rhine catchment.

Water supply – Agriculture

As the largest water consumer agriculture's water needs in the Rhine catchment will adapt to changing conditions. The agricultural sector becomes less intensive, which also means reduced use of fertilizers. New crop types will be cultivated matching the local climate and less intensive cultivation methods. The size of irrigated area will decline in the Rhine countries. Still due to longer dry periods in summer higher abstractions from the Rhine River, groundwater reliance for irrigation will increase during droughts. There are more frequent combinations made between agriculture and nature conservation, and agricultural and other functions, such as tourism. Due to changes in dietary patterns the livestock sector decreases by 15%, whereas arable agriculture only slightly decreases 2% (Estimation 1.2). However, the area that could be irrigated increases with approximately 30% (Estimation 1.3). These are more efficient types of irrigation, such as drip irrigation.

Drinking water

All the countries within the Rhine basin strive for a more efficient use of drinking water. In the future, groundwater and surface water from the Rhine catchment will remain essential for drinking water. Groundwater will predominate due to pollution concerns. A high percentage of the return flow of the water supplied (95%) is collected in sewerage system after use. The European average of water use of 144l/day per person will be reduced to 90l/day per person (Data source). Rainwater is infiltrated in these wells and used to flush the toilet, to clean and wash laundry.

Industrial water

The industry in the Rhine basin stabilizes in the Ruhr area and slightly reduces in the other parts of the basin. The type of industry changes to industry related to the circular economy and data centers. Heavy industry becomes cleaner or is phased out. Water use of the industry is slowly reducing, with a total reduction of approximately 19% (Delta scenarios).

Cooling water

Fossil fuelled power plants are not part of the energy generation anymore, which means that the cooling water demand decreased significantly. Only nuclear power plants and hydrogen production plants make use of cooling water to make energy carriers. The fraction of nuclear power in the energy mix stays the same in the Rhine basin countries. However, along the Rhine most nuclear power plants (names) will be closed in 2035, and there is no replacement foreseen.

Inland water transport

There is a strong cooperation between countries in the Rhine basin. In the future, inland waterway transport (IWT) in the Rhine catchment, will adapt to climate change impacts, with fluctuations in water levels requiring adjustments to infrastructure. The economy is globalized, and there is more focus on sustainable local production. This means that the demand for transportation is stabilizing or for some transportation classes slightly increasing (e.g. containers). All the transport modalities transition towards emission free transport, through electrification or hydrogen. IT on the Rhine will hold a strong position to mitigate climate change by implementing the CCNR roadmap on emission reduction. Sustainable IWT will continue to support economic growth and innovation in the region.

Hydropower

Hydropower generation in the Rhine catchment will face challenges during low-flow periods. Minimum storage and flow requirements will sustain operations, but environmental considerations incl. biodiversity connectivity and minimum environmental flows, will increasingly influence hydropower practices, in addition to managing floods and droughts. The hydropower capacity does not change in 2050.

Mining

The lignite mines in Germany closed in 2035, which led to a temporary water demand to fill the pits. After the pits are filled there is a permanent demand of 0.5-1 m³/s (Estimation 1.6) to restore the groundwater levels until 2200. The demand for natural resources slightly declines, however due to technological development the demand for rare earth materials increases. The lignite mines in Germany will close in the upcoming decades, which will lead to a temporary water demand to fill the pits. For filling the Garzweiler and Hambach lignite mines with water diverted from the Rhine River a schedule has been drawn up for the planned extraction to minimize the effect on the water level (shipping): at low discharges (up to 1000 m³/s) 1.8 m³/s is extracted, increasing to 18 m³/s at Rhine discharges of approximately 2200 m³/s and more (Estimation 1.4). The minimum of 1.8 m³/s is mainly intended for keeping wetlands in the vicinity of the mines wet during dry periods (Estimation 1.5). The excess is for filling the mines. It is estimated that over 25 billion cubic meters of water will be required for the entire project, which will begin in 2030 and extend over several decades. (The pit of Tagebau Inden will be filled with water diverted from the Meuse River basin) (Goodenough et al. 2015).

Water level management and flushing

To tackle the challenges of land subsidence in the Delta, peat oxidation, and salinization exacerbated by rising sea levels, the Rhine catchment will implement advanced flushing and water level management strategies. These measures aim to mitigate the adverse effects of climate change. Specifically, the Netherlands will focus on curbing land-based emissions, particularly from greenhouse gases emitted by meadow areas. This will involve the rewetting of peat meadows to prevent peat oxidation, thereby reducing water demand and fostering environmental sustainability.

Table A.1: Estimations referenced in Narrative 1: Rhine Sustainable Community

Estimation 1.1	Share of renewable energy was based on current trends and the assumption that the share of renewable energy will progress even faster in this scenario.
Estimation 1.2	Livestock sector decreases due to a reduction of meat consumption in this scenario.
Estimation 1.3	The area that could be irrigated increased due to more local agricultural activity internal research memo Deltares.
Estimation 1.4	Increased discharges due to the filling of the lignite mines is based on estimates found for the Meuse internal research memo Deltares.
Estimation 1.5	Minimum flow for wetlands estimated based on internal research memo Deltares internal research memo Deltares.
Estimation 1.6	Water volume demand after filling the pits

A.2.2 Narrative 2: Rhine Middle of the Road

Now in 2050, the “Middle of the Road” scenario has unfolded from moderate trends present in 2020. The Rhine basin has found a balanced economic growth and moderate population growth. The Rhine countries continue to rely on fossil fuels as the primary source of energy, and the transition towards renewable energy sources has been gradual. The moderate economic growth has led to steady, incremental development in various economic sectors. Changes have been evolutionary rather than revolutionary, reflecting a path of continuity and gradual adaptation. The accompanying climate scenario is moderate.



Figure 28: Rhine Middle of the Road – Picture generated with Copilot (16.09.2024)

A.2.2.1. Biophysical Environment

The Rhine catchment is facing more pronounced environmental changes.

Average temperatures have risen significantly, leading to altered precipitation patterns and an increased frequency of extreme weather events. These changes have impacted water availability and quality, affecting both natural ecosystems and human activities. The region's biodiversity and forests are under pressure, with some species struggling to adapt to the changing conditions. Water quality is threatened, and prolonged low flow periods have become more common. Ecosystem health is declining as hydrological patterns become more extreme. Groundwater remains moderately available, but water quality is slightly deteriorating, posing additional challenges for the region.

A.2.2.2. Socio-economic developments

Population growth

Major socio-economic drivers are population growth and urbanization. The human population of the Rhine basin equals 62 million in 2050, many of them crowded in large urban areas extending along the river. Population has grown by 7% (IIASA, 2023 - SSP 2) between 2020 and 2050. Population trends vary between the Rhine countries but are consistently positive apart from Germany. The population in the Rhine catchment with an increase in most countries: moderate population growth for Austria (+4%), France (+6%), Luxembourg (+21%), Netherlands (+3%) and Switzerland (+12%). Germany experienced an overall decline (-3%), whilst having the largest share in the Rhine catchment (IIASA, 2023 - SSP 2).

Urbanization

Even with a slight population growth, this population increase has concentrated in towns and cities, leading to further urbanization. As urbanization continues, current major metropolitan areas, including the largest cities in the Rhine catchment area such as Cologne (1,084,831), Frankfurt (773,068), Rotterdam (671,125), Stuttgart (632,865), and Dusseldorf (629,047), experience population growth (Data from Belz 2022). The economies in the Rhine states are characterized by political stability and well-functioning, globally connected markets. In this scenario, the average urbanization increase is slightly lower at 9%. Austria leads the way with a projected urbanization rate growth of 12%, while France maintains a steady 5% increase.

Both Germany and Switzerland experienced a 11% rise in urbanization. Luxembourg and the Netherlands experienced a 7% increase in urbanization in the past decades (2020-2050). This ongoing urbanization and population growth in major cities underscore the dynamic and evolving nature of the Rhine catchment area (IIASA, 2023 - SSP 2).

Economic growth

Economy is on the rise where Austria and France both saw a growth rate of 1.8%, while Germany experienced a slightly lower growth rate of 1.3%. Luxembourg matched Austria and France with a growth rate of 1.8%, and the Netherlands was slightly ahead with a growth rate of 1.9%. Switzerland experienced a growth rate of 1.4% (IIASA, 2023 - SSP 2). On average, these countries saw an economic growth rate of 1.67%, indicating a steady economy in the Rhine region. The Rhine basin has indeed remained a vital economic hub in 2050. Its globally connected market and strong international relations have played a crucial role in this. Despite the challenges posed by the slow energy transition away from fossil fuels, these countries have managed to continue their economic growth while making significant strides towards a more sustainable future. This journey towards sustainability and economic growth is a testament to the resilience and adaptability of the Rhine countries.

Economic sectors

The Rhine catchment area is a vibrant economic region, characterized by free trade within and between its countries. The European Union's trade relationships with the global market are stable and collaborative, fostering an environment conducive to economic growth. The private sector in this region is expected to grow, further bolstering the economy. Major economic sectors such as manufacturing, agriculture (contributing 0.5%-3.5% to the economy), trade and logistics, tourism, energy, and services (contributing 65%-80% to the economy) continue to drive economic expansion. These sectors are supported by stable markets and the forces of globalization, which facilitate the exchange of goods, services, and ideas. Cities within the Rhine catchment have become hubs of technological development, with a high focus on digital transformation across all economic sectors. This digital transformation is not only improving efficiency and productivity but also paving the way for innovative solutions to economic and environmental challenges. The Rhine River itself plays a crucial role in this economic landscape, serving as a major transport route that accommodates economic growth and trade between the Rhine countries. However, it faces the challenge of more frequent low flow situations, which require careful management to ensure the river continues to support the region's economic activities.

Technology and innovation

Technological advancements have been steady and incremental, mirroring the moderate economic growth of the region. Innovations have primarily focused on increasing water efficiency in companies and households. However, there has been no major breakthrough in innovation. The focus has been on making gradual improvements to existing technologies and systems, rather than on revolutionary changes.

Resource and Energy

Slow efforts are being made to reduce resource and energy consumption, following current trends. The overall share of energy from renewable sources in the Rhine states is currently between 13% and 21%. Specifically, the Netherlands is at 15%, Germany at 21%, Austria leads with 34%, Belgium is at 14%, and Luxembourg at 13% and France 28% (French Ministry Energy Transition) according to (Eurostat 2022). It's anticipated that the overall share of renewable energy increased, albeit at a slow pace.

This gradual shift towards renewable energy sources is a crucial part of the region's strategy for sustainable development and energy security. However, the pace of this transition will depend on a variety of factors, including technological advancements, policy decisions, and market dynamics.

A gradual shift towards renewable energy sources ongoing, reducing fossil fuel dependency and enhancing energy security.

SDG's and EU Green Deal

Policies, goals, and legislation like the Sustainable Development Goals (SDGs), EU Green Deal, and Water Framework Directive are integrated into Rhine catchment policies at a moderate pace. These initiatives, which promote ecological restoration, renewable energy adoption, and sustainable water management, are implemented with some delay. Both economic interests and environmental concerns are given importance, nature and biodiversity are considered alongside other functions. This results in a moderate level of protection for natural areas, including those not part of the Natura2000 network. The growing population and housing demand are met with strategies that balance development and conservation. Industry and agriculture are allowed to expand, but with regulations that limit their impact on natural areas. This results in a maintained natural area in the Rhine basin, which faces manageable levels of pressure from pollution and water extraction. Despite the challenges, the focus is on achieving a sustainable balance between economic resilience and environmental preservation.

Cooperation and decision making

The Rhine countries act based on national law and interest and collaborate through the Rhine Commission. There is no collaborative approach to the management of the water resources, but still common interest in harmonizing the needs in the catchment and addressing challenges. Flood risk management and water quality management will remain a priority, with ongoing efforts to reduce risks and strengthen awareness. Finding solutions in water allocation and prioritization, among different water users and between countries goes slowly. Decisions are made on a national level, based on national water needs. Each country has their own organizational structure, where projects are funded nationally or even regionally.

A.2.2.3. Impacted water related sectors

The Rhine catchment will experience various impacts from both climate change and socio-economic drivers. Biodiversity and forests are under high pressure. Changes in hydrological patterns will threaten water quality during low-flow events, necessitating adaptation strategies and minimum flow requirements. The Rhine is in a drought risk transition area, in which the south of the region is affected first, which will shift to the north in higher climate change scenarios (EEA, 2021). It seems that wetlands in the northern part of central Europe will be less affected by increased variability while the forest ecosystems there will suffer to a greater extent (EEA, 2021). These alterations in hydrological patterns are projected to adversely affect water quality, particularly during low-flow events under high temperatures, further threatening ecosystem integrity. The impacts of these changes are multifaceted and contingent upon local conditions, often necessitating minimum flow requirements and adaptation strategies. Forestry practices, including changes in forest cover, can further influence basin hydrology, altering rainfall distribution, runoff mechanisms, and groundwater-surface water interactions. Understanding the importance of recreational activities and ecosystem services, such as biodiversity conservation, is crucial for prioritizing policy measures and assessing their potential impacts on minimum river flows and water quality standards in the future.

Water supply – Agriculture

All countries are in search for additional sources for water supply, including non-conventional water sources (recycled water, desalinated water, wastewater etc.) and raise of water efficiency and water treatment, and require sustainable management practices to ensure responsible water use. The largest water consumer in the Rhine basin is the agricultural sectors, of which the water needs in the Rhine catchment are growing. Crop cultivation will become more intensive and sophisticated, driven by technological advancements like precision farming. The size of irrigated area will grow especially in Switzerland and Germany. If the demand for biomass from energy crops is met using standard arable crops, perhaps necessitating greater use of irrigation, then agricultural water demand is likely to increase even more. In addition to higher abstractions from the Rhine River, groundwater reliance for irrigation will increase during droughts.

Drinking water

In the future, groundwater and surface water from the Rhine catchment will remain essential for drinking water. Groundwater extraction will predominate for geographical, technical and more complex surface water treatment reasons (surface water pollution). In 2020 most of the drinking water in Germany (66%), Switzerland (80%), Netherlands (60%), France (65%) and Luxembourg (57%) is sourced from groundwater, this remained common practice in the past decades (Estimation 2.1). A high percentage of the return flow of the water supplied (95%) is collected in sewerage system after use (Estimation 2.2).

Industrial water

In the upcoming decades industrial water needs in the Rhine catchment will be shaped by economic and technological factors. While some regions will decrease water consumption through modernization and efficiency, others will experience increases due to a growing economy. Sustainable practices will be increasingly used in managing industrial water demand and ensuring responsible usage.

Cooling water

Power plants in the Rhine Basin will optimize cooling water usage through efficiency measures and technical advancements. Electrification and alternative cooling sources will gradually replace freshwater cooling, driven by climate and socio-economic factors. In total, growing water demand necessitates additional water resources and water efficiency measures, requiring careful water distribution and prioritization.

Inland water transport

In the future, inland waterway transport (IWT) in the Rhine catchment, as a non-consumptive user, will adapt to climate change impacts, with fluctuations in water levels requiring also adjustments to infrastructure such as adjustments to shipping infrastructure and technical adaptation of the fleet. IWT on the Rhine will also continue to mitigate climate change by implementing the CCNR roadmap on emission reduction. Sustainable IWT will continue to support economic growth and innovation in the region.

Hydropower

Hydropower generation in the Rhine catchment will face challenges during low-flow periods. Minimum storage and flow requirements will sustain operations, but environmental considerations incl. biodiversity connectivity and minimum environmental flows, will increasingly influence hydropower practices, in addition to managing floods and droughts.

Mining

Towards 2050 the demand for natural resources will slightly decline, however due to technological development the demand for rare earth materials increases. These materials could be found in the Rhine basin.

The lignite mines in Germany will close in the upcoming decades, which will lead to a temporary (several decades) water demand to fill the pits. For filling the Garzweiler and Hambach lignite mines with water diverted from the Rhine River a schedule has been drawn up for the planned extraction to minimize the effect on the water level (shipping): at low discharges (up to 1000 m³/s) 1.8 m³/s is extracted, increasing to 18 m³/s at Rhine discharges of approximately 2200 m³/s and more (Estimation 2.3). The minimum of 1.8 m³/s is mainly intended for keeping wetlands in the vicinity of the mines wet during dry periods. The excess is for filling the mines. It is estimated that over 25 billion cubic meters of water will be required for the entire project, which will begin in 2030 and extend over several decades (Estimation 2.4). (The pit of Tagebau Inden will be filled with water diverted from the Meuse River basin)

Water level management and flushing

To address land subsidence, peat oxidation and salinization (increased by sea level rise), enhanced flushing and water level management practices will be implemented in the Rhine catchment to mitigate impacts of climate change. In particular, Netherlands' efforts to reduce land-based emissions from the meadow areas (greenhouse gases) by rewetting peat meadow areas to prevent from peat oxidation affects the water demand. The expected reduction in CO₂ emissions from peat meadow areas is approx. between 1.0 and 1.6 Mton CO₂/year when the surface water level is raised towards approx. 20-40 cm below ground level (Estimation 2.5). In the current situation the total water demand for flushing all polders is 20 m³/s. In 2050 it will be approx. 38 m³/s based on sea level rise of approx. 25 cm. (Van der Brugge, R., R.C. de Winter (2024)).

Table A.2: Estimations references in Narrative 2: Middle of the road

Estimation 2.1	Drinking water sources are estimated based on current drinking water sources in 2020.
Estimation 2.2	Realistic return flow in the European region.
Estimation 2.3	Rhine discharges during ignite mine filling are based on estimations from: p.m.
Estimation 2.4	Excess water for filling the ignite mines was estimated from email exchange
Estimation 2.5	Estimation based on the Dutch delta program

A.2.3

Narrative 3: Rhine Economic Growth

The “Global Growth” scenario indicates that by 2050 the Rhine countries place increasing faith in competitive markets, innovation, and participatory societies and strong private sector involvement to drive rapid technological progress and the development of human capital as the path to sustainable development. Global markets are highly integrated, with substantial investments in health, education, and institutions to enhance human and social capital. Simultaneously, the push for economic and social development continues alongside the exploitation of abundant fossil fuel resources and the adoption of resource and energy-intensive lifestyles. National economic interests have taken precedence, leading to a focus on intensive agriculture and a robust Rhine economy with global connectedness.



Figure 29: Rhine Economic Growth – Picture generated with Copilot (16.09.2024)

A.2.3.1. Biophysical Environment

The Rhine catchment is experiencing substantial environmental changes due to significant increases in greenhouse gas concentrations, including those from the (drying) peatlands in the Rhine basin. Higher average temperatures and more extreme weather events have led to severe impacts on water resources, with increased risks of droughts and floods. The natural ecosystems in the region are under considerable stress, with potential loss of biodiversity and shifts in species distributions. The overall health of the Rhine catchment's environment is heavily compromised, affecting both ecological and human systems. Water quality is worsening, and groundwater resources are depleted. There is no minimum flow requirement for the natural environment, exacerbating the challenges faced by the region.

A.2.3.2. Socio-economic developments

Population growth

The growth of the population and urban development are the main elements impacting socio-economic situations. The Rhine basin accommodates 65 million people in 2050. The population has grown significantly with an average pace of 17% (IIASA, 2023 - SSP 5) from 2020 to 2050. The Rhine countries experienced varying rates of population growth. Austria saw a 14% increase, while France's population grew by 10%. Germany had a 5% rise, and Luxembourg experienced a significant 38% growth. The Netherlands reported a 7% increase, and Switzerland's population grew by 25% (IIASA, 2023 - SSP 5).

Urbanization

A high rise in population is largely concentrated in urban regions, further propelling urbanization. The trend of urbanization remains unbroken, with major cities continuing their expansion. The largest cities in the Rhine catchment such as Cologne Frankfurt, Rotterdam, Stuttgart are growing. The Rhine states maintain political stability whilst focusing on global economy and national security. The average increase in urbanization for this scenario is 10%.

Austria saw a 16% increase in urbanization, while France's urbanization grew by 5%. Germany experienced an 11% rise, and Luxembourg had a 7% increase. The Netherlands also reported a 7% growth, and Switzerland's urbanization increased by 11% (IIASA, 2023 - SSP 5).

Economic growth

The Rhine countries are experiencing an increase in economic growth. The GDP growth rates for these countries are as follows: Austria at 3.0%, France at 2.9%, Germany at 2.5%, Luxembourg at 2.8%, the Netherlands at 3.0%, and Switzerland at 2.5% (IIASA, 2023 - SSP 5). The average GDP growth rate for these nations stands at approximately 2.78%. This consistent economic growth highlights the stability and strength of the economies in the Rhine region, contributing significantly to the overall economic landscape of Europe. The economies in the Rhine states are politically stable with functioning and growing international markets. The economic footprint of the population increases, with more use of resources per capita. The international economy also includes the agricultural sector, which leads to the stimulation of high intensity agriculture. The interests of the agricultural sector take precedence over the interests of nature. This leads to a decline of natural areas, such as forests and wetlands.

Economic sectors

In the Rhine catchment area, the focus is shifting towards international orientation, leading to an increase in trade between the Rhine countries and the global market. The private sector is expected to experience high growth, contributing to the overall economic stability of the region. Major economic sectors such as manufacturing, agriculture, trade and logistics, tourism, energy, and services become an even stronger backbone of the economy. These sectors are driving economic expansion, reflecting the region's goal of becoming internationally connected. While environmental protection is not the primary focus in this scenario, the continued growth and development of these sectors are crucial for the economic resilience of the Rhine catchment area. This approach ensures that the region can sustain its economic vitality. This economic growth creates numerous job opportunities as industries expand and new businesses emerge to meet the growing demand for goods and services. The influx of investments in various sectors, particularly in intensive agriculture and industrial activities, further boosts employment rates.

Technology and innovation

Technological advancements are pivotal, with significant investments in both carbon-intensive fuels like coal and unconventional oil, as well as low-carbon energy sources. The high-tech economy thrives, leading to substantial improvements in productivity and living standards. This pathway underscores the dual role of technology as both a driver of economic prosperity and a potential source of environmental challenges.

Resource and Energy

The industry prioritizes global resources and globally connected markets over environmental regulations, contributes to a slow growth in the share of energy from renewable sources in the Rhine states. Despite this, the Rhine countries have seen a slight increase in their renewable energy share, with France at 36%, Germany at 42%, Luxembourg at 26%, the Netherlands at 30%, and Switzerland at 100% (Estimation 3.1). However, no targets have been set to phase out nuclear power and hydropower after 2050. The European energy goal of 2030, which aimed for over 40% renewable energy sources, was not achieved due to lower investments in renewable energy technology and a less ambitious renewable energy strategy. The need for additional energy resources led to an increase in hydropower and nuclear power plants and a slow reduction of fossil-fuelled energy, especially coal. Switzerland will continue to rely on hydropower and with an increasing energy demand also invest in building new hydropower stations.

SDG's and EU Green Deal

Despite the existence of policies, goals, and legislation such as the Sustainable Development Goals (SDGs), EU Green Deal, and Water Framework Directive, their integration into Rhine catchment policies has been limited. These initiatives, which are designed to promote ecological restoration, the adoption of renewable energy, and sustainable water management, have been implemented with significant delays. This slow pace of implementation indicates a lack of prioritization of these laws, leading to missed major milestones. Nature and biodiversity are often given less priority compared to other functions, leading to significant pressure on natural areas, especially those not included in the Natura2000 network. The increasing population and the consequent demand for housing have resulted in more homes being constructed in these natural areas. Additionally, the expansion of industry and agriculture into these areas is also a contributing factor. This has led to a reduction in the size of the natural area in the Rhine basin, which is now under increased pressure due to pollution and water extraction.

Cooperation and decision making

The Rhine River remains the most important waterway for the European economy and is prioritized as such to support economic growth. The focus on decision making revolves around a global economy and the wish to compete internationally. Decisions about water resources are on a national, top-down level with focus on national security. The Rhine countries both collaborate and compete on a global scale striving for their own economic interests. Local communities have no power in decision making and environmental needs are often deprioritized over economic interests.

A.2.3.3. Impacted water related sectors

The Rhine catchment will experience various impacts from both climate change and socio-economic drivers. The public gives less importance to nature and biodiversity conservation. This is reflected in the failure to meet the goals of the EU birds and habitats directives and Water Framework Directives. No new European regulations have been introduced since then. The quality and quantity of natural areas (especially non-Natura2000) is declining (-2% surface area)(Estimation 3.2). This is due to the growing pressure in these areas for housing, industry and agriculture. This results in a decline in water demand for nature in the Rhine basin. This will pose major challenges to the natural environment biodiversity and forests. Recreational areas in the Rhine catchment are declining due to housing shortages and prioritization of national economic interests. Still, the tourist industry in the Rhine remains an important part of the economy and many inhabitants use areas along to river for recreational activities.

Water supply – Agriculture

The agricultural sector becomes more intensive, which implies larger farms, and no change in the use of fertilizers and pesticides. Irrigated area increases with 95% (Delta scenarios), in which the mix of irrigation methods stays the same (e.g. drip irrigation, sprinkler etc.). There is no change in diet in Western Europe, resulting in a similar food demand. The favorable conditions for agricultural production along the Rhine basin in comparison with other regions, results in an increase of agricultural land of 5% (Delta scenarios) At the same time, the population's footprint is increasing, resulting in higher energy and water use. The agricultural sector adapts to the increasing demand and intensifies production on arable and livestock farming.

Drinking water

The drinking water use per person in the Rhine countries stays the same. The increase in efficiency of the drinking water system is offset by the higher use of drinking water in summer.

Furthermore, the strong population increase increases the total drinking water demand. In the future, groundwater and surface water from the Rhine catchment will remain essential for drinking water. Groundwater will predominate due to pollution concerns. A high percentage of the return flow of the water supplied (95%) is collected in sewerage system after use (Estimation 3.3).

Industrial water

In the upcoming decades industrial water needs in the Rhine catchment will be shaped by economic and technological factors. The industry in the Rhine basin is growing fast. Especially along the border between France and Germany. Generally, the industrial sector has to deal with more low flow situations and an increasing demand.

Cooling water

Power plants in the Rhine Basin will optimize cooling water usage through efficiency measures and technical advancements. Still, fossil fuelled power plants remain part of the energy mix, although the number of fossil-fuelled power plants have been reduced by approximately 50% (Estimation 3.4). The power plants along the Rhine will be maintained, to keep up with the increasing energy demands.

Inland water transport

Total consumption increases, which requires (natural) resources. The transport of bulk goods grows as well as container transport. The demand for inland water transport grows more rapidly than other modalities, this results in a strong increase in inland water transport.

Hydropower

Most of the hydropower reservoirs have combined functions, such as for drinking water use, industrial water uses and flood safety. Due to less investments in operation and maintenance of the power plants, the hydropower capacity is reduced. No new hydropower plants are foreseen to be built in this scenario.

Mining

The economic activity is growing, due to large investments in the sub-basin as compensation for the closure of the lignite mines. The closure of the lignite mines in Germany has been delayed, due to national discussions about the importance of energy self-sufficiency and access to natural resources. In 2050 the mines are still open. Countries are searching for new potential of natural resources, as the demand for natural resources increases. This leads to re-opening of former mines, and exploration of new sites for rare earth materials (Goodenough et al. 2015).

Water level management and flushing

To address land subsidence, peat oxidation and salinization (increased by sea level rise), enhanced flushing and water level management practices will be implemented in the Rhine catchment to mitigate impacts of climate change. More flushing will be necessary in this scenario due to a more severe SLR scenario.

Table A.3: Estimations referenced in Narrative 3: Global Growth

Estimation 3.1	Renewable energy share was estimated from current shares in 2020 of the Rhine countries from online sources and press releases.
Estimation 3.2	Natural area declining from Natura 2000?
Estimation 3.3	Return flow collected in sewage is estimated based on: p.m.
Estimation 3.4	Reduction of fossil fuelled power plants is estimated based on: p.m.

B Evaluation and validation of IWRM Rhine tool for the CHR SES / STARS4Water Study in the Rhine basin

B.1 Approach for validating IWRM Rhine modelling framework calculations

To ensure the accuracy and reliability of our IWRM Rhine Modelling Framework, several steps were taken during the validation process. Traditionally, validation involves comparing model inputs and outputs with observed data to assess how well the model simulates real-world conditions. However, due to limited availability and accessibility of observational data—particularly regarding water use and reservoir operations—we adopted an alternative approach. Instead of direct comparison with measured data, we assessed the reasonableness of model outputs by placing them in a comparative context with findings from other studies, reports, and publicly available data sources. In this validation chapter, we quantitatively compare our calculated water demand (i.e. users' requests for water) and water use (i.e. supplied water) with values reported in literature and databases to evaluate consistency and plausibility.

The following studies were selected for comparison based on their relevance and novelty (marked in bold how they will be referenced in this chapter):

- Umweltbundesamt (2024): Abschlussbericht Auswirkung des Klimawandels auf die Wasserverfügbarkeit – Anpassung an Trockenheit und Dürre in Deutschland. (**WADKlim** using DESTATIS Data)
- ICPR (2024): Climate change induced discharge scenarios for the Rhine basin (**HCLIM**).
- Joeres, A., Huth, K., & Steeger, G. (2022). Klimawandel: Wasser knapp – Industrie hat jahrzehntelange Entnahmerechte (**CORRECTIV**)
- The National Database of Quantitative Water Abstractions of France (**BNPE**)
- Daily discharge data from the Global Runoff Data Centre (**GRDC**)

B.2 Hydrological timeseries compared to HCLIM Study

The hydrological timeseries input for the Ribasim model was derived from the Wflow hydrological model, which integrates data from various sources. An extensive calibration and validation of Wflow was previously conducted as part of a project for the Dutch Ministry of Infrastructure and Water Management, within the framework of the Dutch Delta Programme. This validation focused on generating time series for rainfall, evaporation, and river discharge without water demand, representing natural water availability. The model was calibrated against observed discharge data from the E-OBS dataset. For further details, see Buitink et al., 2023.

The historical discharge time series produced in the Delta Programme project were used as input for Ribasim. These time series represent river discharge without explicitly accounting for water demand. Wflow outputs are generated at a daily time step, which are then aggregated to a 10-day time step for use in Ribasim simulations. Table 16 shows that the behaviour of river discharges remains consistent, with and without explicit simulation of water demand, due to the prioritization of domestic water use.

To further validate the discharge simulations, we compared outputs at various locations along the Rhine with discharge time series from other hydrological models compiled in the HCLIM study (ICPR, 2024). The HCLIM study aims to improve understanding and management of climate change impacts on hydrological systems in the Rhine catchment. It evaluates discharge projections from different models and scenarios, develops standardized methods for integrating data across countries and institutions, and enhances extreme value statistics. Notably, HCLIM is based on IPCC AR4 and AR5, while the CHR SES study uses the latest AR6 projections.

Table 16 compares the projected future changes in discharges from the HCLIM study at three locations with the calculated discharges in with and without simulating water demand explicitly. The comparison shows that the expected changes are within the same order of magnitude, with average projected changes around 20% in both studies.

Table 16: Comparison HCLIM and Wflow-Ribasim Rhine discharges

Indicator	Gauge	HCLIM			Wflow	
		Observed values (m3/s)	Observed change (%)	Projected change near future (%)	Projected near future (%)	
		Reference 1980-2010	Present 1991-2020	2031-2060*	KNMI'23 2050*	KNMI'23+SES 2050 (incl. water demand)
NM10Q Annual	Lobith	1124	-5	-31 to +3 (-19 to -3)	-22 to -11	-22 to -10
	Kaub	881.8	-5	-29 to +5 (-15 to 0)	-21 to -9	-19 to -10
	Basel	533.8	-3	-32 to +9 (-3 to -2)	-16 to -2	-15 to -1
NM10Q Summer	Lobith	1191	-4	-33 to 0 (-22 to -2)	-22 to -14	-21 to -11
	Kaub	974.3	-5	-35 to +1 (-19 to -2)	-21 to -14	-20 to -14
	Basel	660	-2	-35 to +5 (-7 to -5)	-20 to -8	-19 to -7
Average Annual	Lobith	2324	-6	-11 to +11 (-4 to +10)	-6 to +2	-6 to +1
	Kaub	1745	-5	-13 to +13 (-5 to 6)	-6 to +1	-6 to +1
	Basel	1073	-3	-15 to +11 (-6 to -5)	-4 to 0	-4 to 0
Average Summer	Lobith	1074	-5	-29 to +4 (-19 to -3)	-13 to -5	-11 to -6
	Kaub	836.1	-4	-27 to +6 (-15 to -1)	-13 to -6	-12 to -6
	Basel	504	-1	-32 to +8 (-)	-11 to -5	-11 to -5

*Plotted in a visual comparison in Figure 30

The comparison between KNMI'23 2050 and KNMI'23+SES 2050 scenarios shows that the ranges of projected discharge changes do not differ significantly. In three instances, both scenarios show equal ranges. In five cases, KNMI'23 2050 exhibits larger ranges, while in four cases, KNMI'23+SES 2050 has the larger range.

Given the overall similarity in outcomes, KNMI'23 2050 was selected for a more detailed comparison with the HCLIM study. This allows for a focused analysis of discharge projections using a consistent climate scenario framework shown in Figure 30.

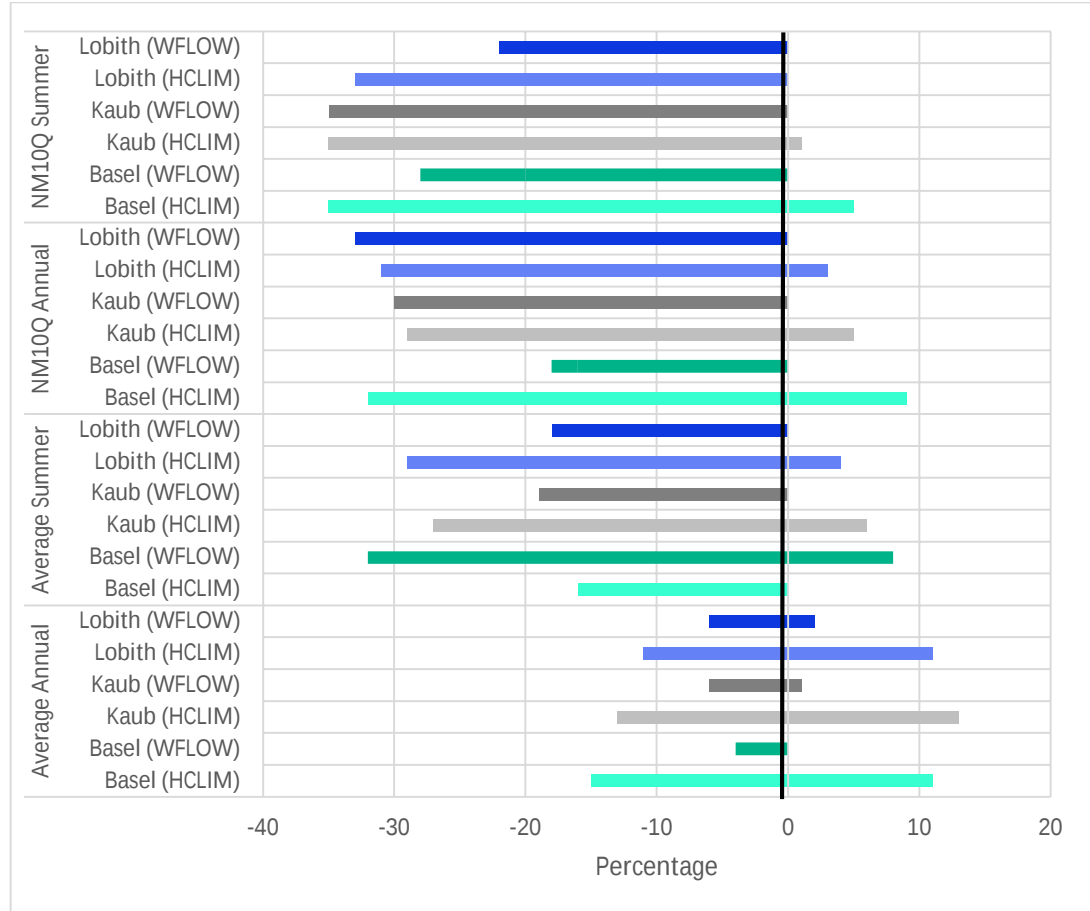


Figure 30: Comparison Projected Future Changes per Gauge in HCLIM and WFLOW

The range in change in annual discharge is larger for all locations in the WADKlim study. Both studies predict a decline in discharge for the average summer, with variations within the same order of magnitude. However, the HCLIM study predicts lower minima for both Lobith and Kaub. For the Annual NM10Q (Normal Minimum over 10 Days), the results are very similar for both Lobith and Kaub, while Basel shows a larger range in the HCLIM study. The Summer NM10Q results are again very comparable between the two studies.

B.3 Water use of the domestic sector compared to WADKlim

Table 17 compares our calculated domestic water demand with estimates from the WADKlim study for both the current situation and future scenarios. For the public sector across Germany, WADKlim estimates a demand of 152.2 m³/s, while our Ribasim-based calculations for the entire Rhine catchment amount to 76.4 m³/s. The WADKlim study suggests a higher domestic water demand than assumed in Ribasim Rhine model.

Table 17: Current Public Water Demand vs. Domestic Water Demand

Projected non-public Water Supply Germany (WADKlim Figure 19)				Ribasim Domestic Use Demand	
Scenario	Year	Mrd. m ³	m ³ /s	Scenario	m ³ /s
Real (black)	2019	4.8	152.2	Current Situation	76.4
Scenario 1 (blue)	2050	5.1	161.7 (+6%)	Rhine Global Growth	84.9 (+11%)
Scenario 2 (red)	2050	4.9	155.4 (+2%)	Rhine Middle of the Road	74.3 (-3%)
Scenario 3 (green)	2050	4.2	133.2 (+14%)	Rhine Sustainable Community	62.7 (+22%)

The comparison of domestic water demand for the current situation shows that our modelled values are within the same order of magnitude as those reported in the WADKlim study. The higher domestic water demand estimated for Germany as a whole is likely due to its larger population (approximately 84 million) compared to the 58 million people living within the Rhine catchment. Additionally, the Rhine basin includes parts of Switzerland, Liechtenstein, Austria, Germany, France, Luxembourg, and Belgium, which contributes to differences in aggregated demand. It is also important to note that the Ribasim estimates exclude the Delta Rhine (The Netherlands), which would otherwise add approximately 25 m³/s to the total domestic water demand for the entire Rhine catchment.

Comparing future scenarios between the two studies is challenging due to differences in underlying assumptions. However, the trend and magnitude of change appear broadly comparable. In Scenario 1, both studies project an increase in domestic water demand of around 6–11%. Scenario 2 shows minor changes, with differences of -3% to -2%, while Scenario 3 indicates a significant increase in both studies, ranging from 14% to 22%. To further validate the domestic water use estimates for the Rhine catchment, we conducted a simplified calculation based on national water use data and the share of population living within the catchment. This approach aimed to verify whether our modelled values are within a reasonable range. For this calculation, we used population estimates and average daily water use per person for Switzerland (3 million), Germany (30 million), France (10 million), and the Netherlands (15 million). The average daily water use per person was assumed to range between 125 and 160 litres, depending on the country. These values were then converted to annual water use and expressed in cubic meters per second (m³/s) to allow for comparison with model outputs.

Table 18: Comparison domestic water use

Country	Daily Water Use per Person in Country (liter)	Population in Rhine Catchment (million)	Water Use (m ³ /s)	Source
Switzerland	160	3	5.6	Schumann et. al (2021)
Germany	100-125	30	39.0	
France	125-150	10	15.9	
Netherlands	125-150	15	23.87	
Total	-	58	84.4	-

The calculations performed with Ribasim were more complex than the assumptions made in the above table, as they included other parameters such as temperature resulting in a seasonal variation. When calculating the average domestic water use from the 10-day water use then the results closely match. The average domestic water use in Ribasim was 84.9 in Ribasim which is very close to the estimation above.

B.4 Water use of the industrial sector compared to CORRECTIV

A study by CORRECTIV a non-profit media organization known for investigative journalism in Germany has investigated the largest water users in each German state. They requested data from all 16 states about the biggest private water consumers. While some of the largest users were previously made public, they now present an almost complete picture. Some states, like Rhineland-Palatinate, provided incomplete lists, citing business confidentiality concerns which reflects gaps in data accessibility. A simple validation of the Ribasim industrial water use estimates was conducted with this dataset. Figure 31 shows the overlap of our sub-catchment areas and the administrative boundaries of German Bundeslaender and Rhine Sub-Catchments.

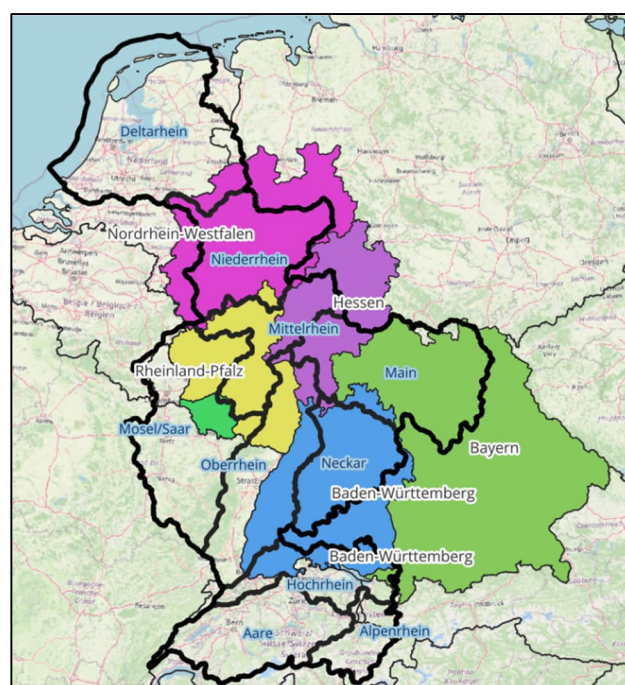


Figure 31: Overlap Germany Bundeslaender and Rhine Sub-Catchments

Table 19: Comparison industrial water use

Biggest Industrial Users (CORRECTIV Dataset)		Industrial Water Use (Ribasim Current Situation)				
District	Water Use m ³ /s	Sub-catchment	Water Use m ³ /s	In Bundes-land	% is in Bundes-land	Water Use m ³ /s
Bavaria (BY)	2.3	Alpine Rhine	7.2	BY	0	0
Baden-Wuerttemberg (BW)	52.0	High Rhine	17.6	BW	50	8.8
		Upper Rhine	57.8	BW, RP	60	34.7
Rhineland-Platinat (RP)	50.8	Moselle/Saar	43.7	RP, SA	30	13.1
Saarland (SA)	50.8	Neckar	33.9	BW	100	33.9
Hesse (HS)	0.6	Main	56.0	HS, BY	100	56.0
North Rhine-Westphalia (NRW)	18.8	Middle Rhine	19.7	NRW, RP	100	19.7
		Lower Rhine	52.0	NRW	100	52.0
Sum	175.2	Sum	287.8	-	-	218.1

The water use or consumption in Ribasim is calculated based on the available water per timestep. The CORRECTIV Dataset only shows the largest water users, so it is possible that this represents 60 or even 90 percent of the overall consumption. Additionally, we are comparing data from Germany to the entire Rhine catchment, which includes France and Switzerland, both likely having significant water consumption. This broader scope could explain the higher estimation from Ribasim, as it accounts for industrial areas and cities from all countries in the Rhine catchment. However with this comparison we can conclude that we have stayed in the same order of magnitude in comparison to the data collection of CORRECTIV.

B.5 Water supply and use agricultural Sector compared to BNPE and WADKlim

Current irrigation water use for agriculture that is used in the Ribasim simulations is calculated using the Wflow water demand and water abstraction module. The Wflow model requires meteorological inputs, including temperature, precipitation, and potential evapotranspiration, which influence crop water requirements and the availability of root zone soil moisture. It then calculates the net irrigation water demand for each area designated as irrigated in the input data. The irrigated area data used in this model comes from Purnamasari et al. (2025), which has been validated against reported total irrigated area at NUTS level 2 regions (Figure 32).

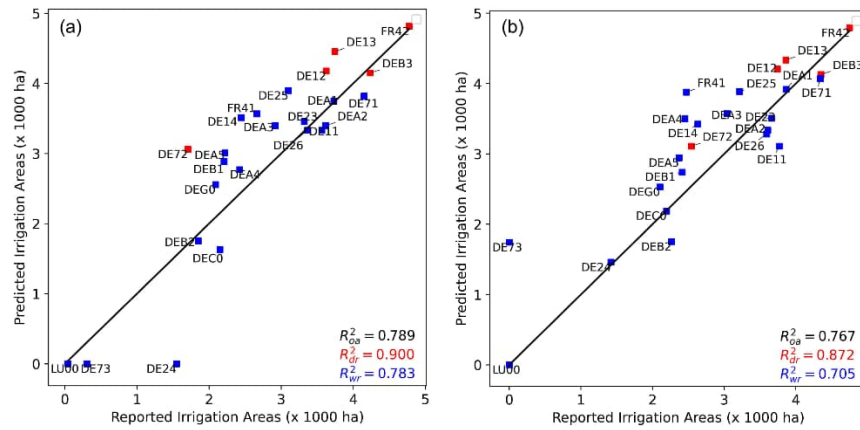


Figure 32: The comparison between the classification results of irrigated area and the reported total irrigated areas obtained from Eurostat data at NUTS level 2 for (a) 2013 and (b) 2016. R^2 values are shown for the overall regions (R^2_{oa}), dry regions (R^2_{dr}), and wet regions (R^2_{wr}).

To validate the simulations for present conditions, the reported irrigation data from the National Database of Quantitative Water Abstractions of France (BNPE, 2025). There are two major irrigated regions in France: Bas-Rhin and Haut-Rhin as shown in Figure 33 and Figure 34. From these figures it can be seen that simulated net water use follows the pattern of the observed irrigation water use over the years. The overestimation of irrigation water use can be attributed to the overestimation of irrigated area and the mismatch between the spatial resolution of the hydrological model and the actual are of irrigated fields. The hydrological model simulates irrigation water use at 1 km resolution, where in reality, not all the fields within one grid cell are fully irrigated. Comparison between simulated and observed water irrigation water use for the Bas-Rhin and Haut-Rhin.

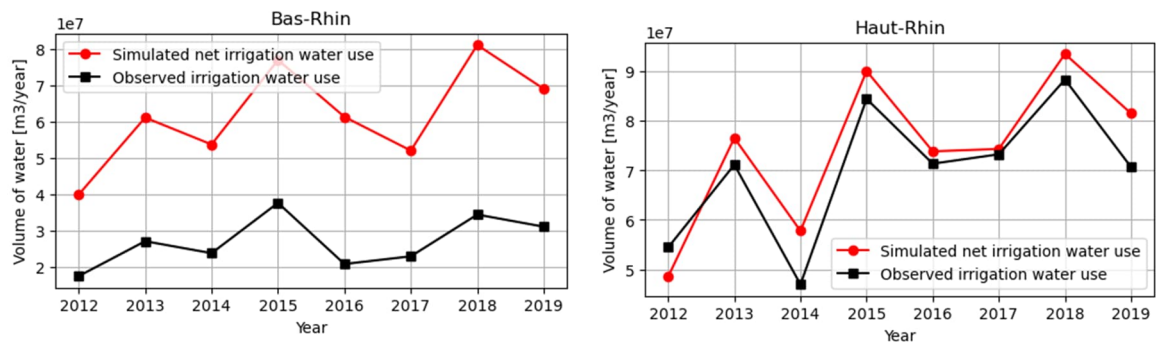


Figure 34: Estimates of irrigation water use for Bas Rhin Figure 33: Estimates of irrigation water use for Haut-Rhin

Determination of the actually irrigated areas and irrigation quantities in the country. The irrigation module in the mGROWA water balance model was used in the WADKlim study to calculate the water quality for the eight crops: wheat, winter barley, rye, rapeseed, potato maturity group (RG) 3, early potato maturity group (RG 1), sugar beet, and maize. The theoretical irrigation requirements of the eight crops cannot yet be directly used in further analyses, such as calculating water use indices. Therefore, the simulation results must first be converted into representative estimates of the actual water required for irrigation in the NUTS 3 regions.

To do this, the simulation results were combined with two data sets:

- the spatial distribution of the crops and
- the areas equipped for irrigation.

To convert the theoretical irrigation demand across all agricultural land into actual irrigation volumes, the data on the size of areas equipped for irrigation published by the federal states for NUTS-3 regions were used. Figure 35 shows the percentage of areas equipped for irrigation as a percentage of total agricultural land in 2019. The grid cells in each NUTS-3 region with the highest theoretical irrigation demand during the period from 1991 to 2020 were classified as equipped for irrigation, so that the total area equipped for irrigation in each NUTS-3 region corresponds to the reported statistics.

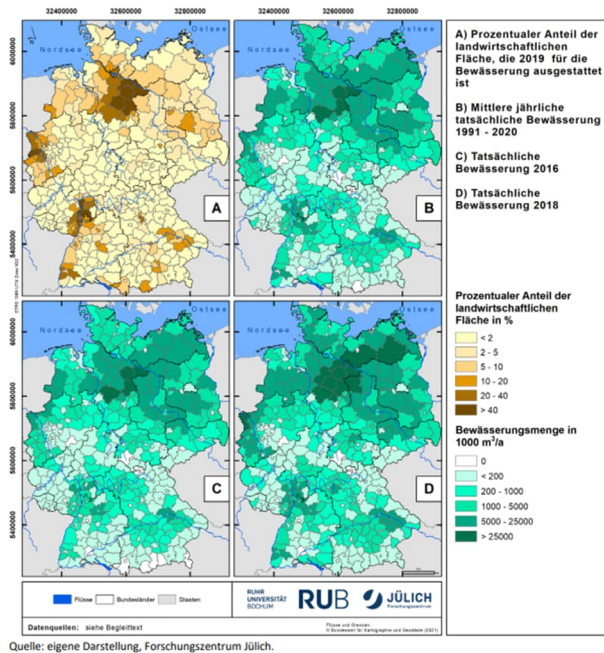


Figure 35: Irrigation volumes (Figure 17 in WADKlim)

B.6 Water demand in different scenarios compared to WADKLIM

The WADKlim study investigates the impact of climate change on water availability and explores adaptation strategies for drought and dryness in Germany. Water use data is based on water management statistics from the Federal and State Statistical Offices, which are updated every three years and collected separately for the public and private sectors. Public water supply primarily serves drinking water needs, while private water supply includes businesses that either produce at least 2,000 m³ of water annually or purchase at least 10,000 m³ from third parties. These data are available through the Germany Regional Database.

Table 20: Comparison non-public water supply Germany with industrial water demand Rhine catchment

Projected non-public Water Supply Germany (WadKlim Figure 20)				Industrial Water Demand Rhine Catchment (wflow-Ribasim)	
Scenario	Year	Mrd. M3	m3/s	Scenario	m3/s
Real (black)	2019	14	443.9	Current Situation	468.19
Scenario 1 (blue)	2050	13	412.2	Rhine Global Growth 2050	608.6
Scenario 2 (red)	2050	9	285.4	Rhine Middle of the Road 2050	421.4
Scenario 3 (green)	2050	8	253.7	Rhine Sustainable Community 2050	280.9

Table 20 compares our calculated industrial water demand with the projected water delivery of the non-public water supply (industrial sector) from the WADKlim study. The WADKlim study provided this data for the current situation and three scenarios.

The comparison between the WADKlim projections for non-public water supply in Germany and the industrial water demand simulated by wflow-Ribasim for the Rhine catchment reveals notable differences in magnitude and spatial scope.

For the current situation (2019), WADKlim estimates a non-public water supply of 443.9 m³/s, while Ribasim calculates an industrial water demand of 468.19 m³/s. The difference of approximately 5.5% suggests a close alignment, especially considering the broader geographic coverage of Ribasim, which includes parts of France, Switzerland, and other upstream regions beyond Germany.

As already mentioned earlier, comparing future scenarios between the two studies is challenging due to differences in underlying assumptions. However, the magnitude of change appears broadly comparable. In Scenario 1 (blue), WADKlim projects a slight decrease in supply to 412.2 m³/s, whereas Ribasim estimates a significant increase in industrial demand to 608.6 m³/s under the Rhine Global Growth scenario. This divergence likely reflects differing assumptions about economic expansion, industrial activity, and water efficiency measures.

In Scenario 2 (red), WADKlim anticipates a moderate reduction to 285.4 m³/s, while Ribasim estimates 421.4 m³/s under the Rhine Middle of the Road scenario. The gap suggests that Ribasim assumes more sustained industrial activity or less aggressive water-saving measures compared to WADKlim.

Both models project the lowest values in Scenario 3 (green), with WADKlim estimating 253.7 m³/s and Ribasim 280.9 m³/s under the Rhine Sustainable Community scenario. The relatively close values indicate convergence in assumptions about reduced industrial water demand due to sustainability-oriented policies.

Due to the limited availability of underlying datasets and reliance solely on the tabulated information provided in the report, a detailed comparison at the country level could not be conducted.

The observed deviations between the WADKlim projections and Ribasim simulations can be attributed to several factors. First, the spatial scope differs: WADKlim focuses exclusively on

Germany, while Ribasim covers the entire Rhine catchment, including parts of Switzerland, France, and other upstream regions, which naturally results in higher aggregate water demand figures.

Second, the scenario narratives and modelling approaches vary significantly. WADKlim scenarios are based on statistical extrapolations and the WaterGAP3 model, incorporating national-level socio-economic and policy assumptions. In contrast, Ribasim uses a process-based hydrological model (wflow) combined with socio-economic scenarios tailored to the Rhine basin, which may include different assumptions about industrial growth, water efficiency, and climate impacts. Third, data resolution and sectoral definitions may differ; for example, WADKlim distinguishes between public and private water supply, while Ribasim aggregates industrial demand across multiple sectors and countries. These methodological and conceptual differences explain the divergence in projected values, especially under future scenarios.

B.7 Validation conclusions

This annex has presented a comprehensive validation of the IWRM Rhine Tool outputs with findings from recent studies and publicly available datasets. Given the limited availability of observational data, a comparative approach was adopted to assess the plausibility and consistency of modelled water demand and use across sectors.

The comparison with the **HCLIM** study confirmed that Ribasim discharge simulations are within the same order of magnitude as other hydrological models, with projected changes aligning closely under similar climate scenarios. The prioritization of domestic water use in Ribasim ensures stable discharge behaviour, even when water demand is explicitly simulated.

For the **domestic sector**, water use estimates were validated against the **WADKlim** study and simplified population-based calculations. The results showed strong alignment, with average domestic water use reinforcing the reliability of the model's assumptions and allocation mechanisms.

In the **industrial sector** water use estimates were compared with the **CORRECTIV** dataset and WADKlim projections revealed that Ribasim outputs are consistent with reported water use figures, despite differences in geographic scope and data completeness. The broader coverage of the Rhine basin in Ribasim explains the higher aggregate values, while the comparison confirms that the model remains within a plausible range.

For **agriculture** water use and supply validation using the **BNPE** dataset and irrigated area classifications demonstrated that Ribasim's irrigation module captures spatial and temporal patterns of water use reasonably well. Minor overestimations were attributed to resolution mismatches and assumptions about irrigated area coverage.

Across all sectors, the comparison of future scenarios between Ribasim and WADKlim showed broadly similar trends in water demand, although differences in scenario narratives and underlying assumptions led to some deviations. These differences highlight the importance of transparent documentation and harmonization of scenario frameworks in transboundary water modelling.

In conclusion, the validation exercise confirms that the IWRM Rhine tool provides a robust and credible representation of water demand and use in the Rhine basin. The model's outputs are consistent with external datasets and literature, supporting its application in integrated water resources management and scenario analysis for the CHR SES / STARS4Water study.



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